Effects of Cutaneous Cueing on Step Initiation Anticipatory Postural Adjustments in Stroke Survivors

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Dedication

This dissertation is the product of ongoing sacrifices, unending flexibility and unwavering love of those around me.

To Aaron…none of this would have been possible without your endless support. Thank you is inadequate. I love you.

To Emmett, Lucy and Keegan…for all of the missed story times and weekends without Mom. Now I'm back – and happier than ever. I love you.

To Mom, Bridgid and Mullen…thanks for finding the humor in everything about this process.

To Dad…I know you would be proud…but not particularly impressed. Wish you were here to see it all end.

Abstract

Step initiation is preceded by a series of electrical and mechanical events that constitute what are commonly termed anticipatory postural adjustments (APAs). These APAs are highly predictable in persons without neuromuscular or musculoskeletal impairments and are known to be advantageously influenced with sural nerve stimulation. Anticipatory postural adjustments in the stroke survivor population have been rarely studied and are poorly understood. Furthermore, the influence of sural nerve cueing on step initiation in stroke survivors has not been explored. This study investigated step initiation APAs in stroke survivors (n=15) in a reaction time paradigm under two "go" cues: (1) sural nerve stimulation; (2) visual light onset. Subjects performed 30 steps with each leg given randomly assigned go cues. Four primary outcomes were assessed: (1) Loading forces; (2) COP excursions; (3) EMG activity in bilateral tibialis anterior and gluteus medius muscles; (4) Reaction times of loading forces, COP and EMG onsets. Sural cueing significantly increased vertical loading, COP and EMG reaction times across all conditions of the stepping trials. The sural cue also produced significantly faster vertical loading compared to a visual cue. The loading amount and speed, EMG activity and net COP displacement were significantly influenced by the stepping condition (paretic or non-paretic). The results of this study are the first to report the ability to improve both reaction times and various aspects of the APA with sural cueing in a stroke population. In that prolonged reaction times are believed to be a major predictor of falls and APAs are diminished in stroke survivors, these results encourage training studies for improving reaction times and APAs.

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Chapter 1: Introduction

Falls among the elderly are frequent and often life-changing. Nearly 30% of individuals over the age of 65 will report a fall within the previous year. [1] Among adults older than 65 years of age, falls account for the most injury-related visits to the emergency department and are the most common cause of accidental deaths. [2] Furthermore, fall status has been significantly associated with nursing home placement. [3] Fall prevention will take on a new urgency as the population ages. By the year 2030, persons 65 years and older will represent 19% of the population (72.1 million individuals). [4]

Frequent falls however are not isolated to individuals over 65 years and otherwise healthy. Stroke survivors for instance are at an increased risk for falls at all stages of recovery. A reported 14-65 % of stroke survivors fall at least one time during the initial hospitalization or rehabilitation stay. [5-7] Up to 73% of stroke survivors reported at least one fall up to six months after hospital discharge. [8-10] Chronic stroke survivors continue to be twice as likely to experience a fall. One study found that 23% stroke survivors with a mean of 10 years post-stroke and living at home fell at least one time in a four month assessment period compared to 11% of age and sex-matched controls. [11]

In order to prevent a fall, a rapid shift (i.e. step) is necessary to maintain control of the center of mass over the base of support. Step initiation in the elderly is known to be altered from their younger counterparts. For example, older subjects were shown to have reduced backward displacement of the COP during the initiation of stepping. [12] The coordinated timing of lower leg muscles were found to be more disturbed in healthy

elderly subjects compared to young adults. [13] An important study that investigated the relationship between stepping reaction time and fall prediction in community-dwelling elderly found that stepping reaction time was the strongest predictor of falls. [14]

Essential components of step initiation are the anticipatory postural adjustments (APAs) made prior to any visible movement or stepping. These preparatory postural adjustments prepare the body to execute a proficient first step. The kinetic and kinematic events that comprise step initiation APAs are more comprehensively documented in non-neurologically involved adults. [15-24] Conversely, studies investigating the APA characteristics of stroke survivors are more variable and less comprehensive. [25-30]

There is growing evidence regarding the malleability of many APA components, including reaction times. [31,32] Given the fact that stroke survivors are at an increased risk to fall and often struggle to regain the ability to walk, it seems important to understand how step initiation APAs are produced in persons with a stroke as well as how the APAs may be influenced with cueing. Such information may lead to rehabilitation strategies, aimed to reduce falls and improve walking ability, that are grounded within scientific evidence. Therefore, the purpose of this experiment is to elucidate the kinetic and kinematic characteristics of step initiation APAs in stroke survivors and investigate how the APAs are influenced by external cueing in a reaction time paradigm.

Chapter 2: Background

Anticipatory postural adjustments (APAs)

Upright walking necessitates the initiation of a first step. A successful first step is preceded by a series of predictable neuromuscular, kinetic and kinematic events known as anticipatory postural adjustments (APAs). Although undetected with visible body movement these muscular, coupled center of pressure (COP) and center of mass (COM) movements and force production events are important precursors to stable and efficient step initiation. Knowledge of the underlying mechanisms of quiet stance is fundamental to understanding the mechanisms necessary to take a step.

An inverted pendulum model is a broadly accepted model describing quiet stance. [33] According to this model, the body acts as an inverted pendulum pivoting about the ankle joint. To maintain quiet standing balance, the COM and COP are tightly coupled with the COP oscillating on either side of and slightly behind the COM. [33] This tight coupling of the COP and COM maintains the COM within a desired position for quiet stance. Consequently, to take a step the COM and COP must become sufficiently decoupled such that the COM moves outside the base of support. The APA creates sufficient decoupling of the COM and COP through which the body releases a step.

The constellation of events that comprise the APA in healthy individuals is well documented. [15-18] Mechanically, the APA consists of a brief increase in the stepping limb vertical ground reaction force concurrent with a posterior and lateral displacement of the net COP towards the stepping limb. The normally tonic activity of the stance limb soleus muscle is inhibited followed by the onset of tibialis anterior (TA) muscle activity in both

the stance and stepping limbs. [19-21] This coordinated muscle activity in the distal leg muscles is believed to be responsible for the initial COP backward displacement. [17,20-22] The amplitude of this initial TA burst was found to have a strong correlation (r = .82) with the amount of posterior COP displacement. [20] However, due to the biomechanical disadvantage of the small TA muscle and its distal location, it is unlikely a major contributor to the medial-lateral shift of the COP. Evidence suggests that the co-activation of the swing limb gluteus medius (GM) and the stance limb adductor magnus (AM) produces a rotary motion sufficient to load and unload (in the medial-lateral direction) the swing limb and stance limb, respectively. [18,23] In summary, the initial COP displacement towards the impending stepping limb in concert with a simultaneous loading of that limb produces sufficient propulsion of the COM towards the impending stance limb in preparation for a first step.

Factors Influencing Anticipatory Postural Adjustments

Step initiation APAs can be altered under a number of naturally occurring/non-experimental circumstances. Stepping speed, age, loading symmetry (or asymmetry) of quiet stance, and neurologic movement disorders can all impact step initiation APA production. Depending on the alteration of the APA, one's step initiation may be enhanced or diminished. Understanding these influencing factors lends insight in to the flexibility of the APA.

The age of an individual and the speed at which the step is initiated can influence the APA. Slower speeds of limb flexion from a quiet stance resulted in smaller vertical ground reaction forces as well as reduced and delayed EMG output. [18,34] This change in

force production is a consequence of Newton's law, F= ma. If a given mass stays constant and the acceleration increases or decreases, ground reaction forces will increase or decrease respectively. The posterior COP displacement in an APA has been shown to be greater at faster stepping speeds compared to "slow" or "normal" stepping speeds. [22] Furthermore, the ability to initiate a step to an imperative visual cue is reduced in the elderly and found to be a strong predictor of falls. [14]

Individuals with movement or balance disorders often demonstrate altered step initiation APAs. Persons with Parkinson's disease are known to have APAs that are prolonged, show reduced swing limb loading, and profoundly reduced COP excursions particularly in the posterior direction. [35-37] Children with hemiplegic cerebral palsy demonstrate a reduced lateral COP shift and reduced anterior tibialis activity during the APA compared to children with typical development [38]. Elderly individuals with unilateral vestibular dysfunction had reduced posterior and medial-lateral (towards the stance limb) COP movement, an exaggerated corrective anterior COP movement and absent tibialis anterior burst during the APA. [39]

Step initiation APAs can also be altered in healthy individuals who (intentionally) stand asymmetrically. Under a reduced loading condition of the stepping limb (20-40% of body weight), the APA of healthy individuals showed reduced amplitude of vertical ground reaction forces under the stepping limb, decreased posterior and lateral excursion of the COP, and increased step duration. [40] Conversely, when the stepping limb was asymmetrically *loaded* (55-70% of body weight), peak loading amplitudes increased, step duration decreased, and COP excursions increased. Although increased loading of the stepping limb demonstrated a more robust APA, maximal loading (>70% body weight)

actually reversed some of the positive effects on the APA. These studies of asymmetrically loaded individuals are important because they investigated a condition commonly observed clinically in neurologically involved persons, such as those with hemiplegia due to stroke.

Individuals post-stroke who have hemiparetic deficits have postural and movement asymmetries including those associated with gait and gait initiation. [41-45] Studies on persons with hemiparesis due to stroke also illustrate neuromuscular and biomechanical alterations in step initiation APAs. For example, stroke survivors who stood asymmetrically (25% body weight on paretic limb) and were stepping with the paretic limb had significantly reduced stepping limb loading, reduced COP displacement and reduced tibialis anterior (TA) activity in the stepping limb compared to post-stroke individuals standing symmetrically. [46]

One study investigating individuals post-stroke performing single leg flexion found spatial and temporal differences related to paretic and non-paretic limb contributions to lateral horizontal ground reaction forces. [29] When the paretic limb flexed, 70% of the resultant horizontal propulsive impulse came from the non-paretic, impending stance limb. Conversely, when the non-paretic limb flexed, 86% of the resultant horizontal propulsive ground reaction forces came from the flexing, non-paretic limb. So, regardless of which leg was flexing the non-paretic limb was the primary contributor to the movement. This apparent dominance of the non-paretic limb is evidence that the central nervous system and its connections found a way to achieve the desired goal (i.e. flex the limb) despite the impairments related to hemiparesis. Although

not reaching statistical significance, half of the subjects in this study had delayed onset of GRF changes under the paretic limb as compared to the non-paretic limb.

Individuals with hemiparesis due to stroke were found to have differences in step and APA characteristics depending on what leg initiated the step. [26] Subjects who stepped with the non-paretic limb had a shorter overall step length and swing time while exhibiting large oscillations of COP excursions in the medial-lateral direction during the APA. The authors interpreted the large COP oscillations as a sign of instability during the step preparation when stepping with the non-paretic limb. In contrast, stepping with the paretic limb resulted in a significantly longer step length and swing time, as well as significantly less COP displacement in the medial-lateral direction during the APA. When hemiparetic subjects were allowed to self-select the time and speed of step initiation, the overall duration of the APA was significantly longer when stepping with the paretic limb as compared to stepping with the non-paretic limb [27]. This delayed execution of the APA may be related to the longer onset latencies and decreased EMG activity in the hip abductors and adductors of hemiparetic individuals during step initiation. [47]

APAs and Cueing

There is a growing body of evidence suggesting that APAs and stepping reaction times can be positively influenced with external stimuli. The majority of the investigations of step initiation and cueing have studied healthy individuals. One study investigated the effects of different go cues (light, sound, cutaneous stimulation) on APA characteristics and reaction times in healthy young and older adults. [12] These authors

found that when the cutaneous go cue (sural nerve stimulation) was given to initiate a step, the medial-lateral displacement of the COP was significantly increased across groups (older and younger) by an average of 16%. A more recent study investigated the influence of two different go cues (visual and sural stimulation) on a number of APA characteristics in healthy adults. [31] Measurements included the timing and magnitude of the ground reaction forces, tibialis anterior and gluteus medius muscle electromyography (EMG), and COP displacement. Given a sural go cue, subjects demonstrated an earlier onset, larger peak, and faster rate of rise of the vertical force before stepping. Muscle activity was also enhanced with more robust and earlier onset EMG activity of both the TA and GM muscles with the sural cue. Finally, sural cueing produced on average, a 22% greater posterior displacement of the COP. A recent PhD dissertation from our laboratory replicated the aforementioned findings with healthy, young adults and found EMG, loading force amplitude, onset time and rate of rise were all significantly enhanced in the APAs of voluntary stepping under reaction time conditions with a sural go cue versus a visual go cue. [48]

An auditory startling stimulus has also been found to alter step initiation APAs in healthy adults. [32] When delivered simultaneously with an imperative go cue, the startling stimulus resulted in a significantly shortened onset of EMG activity in all of the monitored muscles (soleus, TA, rectus femoris), significantly shortened duration of EMG activity in the TA muscle and significantly increased amount of EMG in the rectus femoris muscle. These data suggest that startling cues may generate a more compact burst of muscle activity during the APA.

An exhaustive literature search yields little information regarding the influence of cueing on step initiation APA production in persons with neurologic deficits. One study investigated cueing effects on step initiation APAs in persons with Parkinson's disease. A light electrocutaneous cue to either the hand or earlobe of people with Parkinson's disease enhanced aspects of the stepping APA regardless of the influence of Levadopa therapy. [49] The cutaneous go cue increased not only the amount of vertical swing limb loading but also the speed at which the limb was loaded. The overall effect on the APA and stepping characteristics with the cutaneous cue made the APA of the person with Parkinson's in an "off" state of Levadopa use nearly indistinguishable from controls and those in an "on" state of medication use. This evidence suggests that cutaneous cueing may help enhance step initiation APAs in persons with step initiation difficulties due to neurologic pathologies.

Chapter 3: Purpose

Stepping mechanisms, including APAs, can be impaired in a number of populations including healthy elderly and neurologically involved individuals. These impairments have a variety of implications including increased fall risk and gait initiation difficulties. Understanding how step initiation APAs can be altered to release a step faster, easier, or more efficiently may ultimately lead to novel rehabilitation approaches in a broad range of patient populations. In particular, interventions that assist with an earlier release of a first step in stroke survivors may hasten gait recovery by normalizing kinetics and kinematics of step initiation. Furthermore, a more rapid step release may

improve balance recovery from unpredictable perturbations thereby reducing fall incidence.

The purpose of the study was to elucidate the characteristics of step initiation APAs in stroke survivors and investigate the effects of cueing on APA production during a voluntary stepping task under reaction time conditions.

Aims and Hypotheses

Aim 1: To compare and describe APAs associated with step initiation of individuals with hemiparesis due to stroke for two different go cues (visual and sural stimulation)

Hypothesis 1: Reaction times for vertical ground reaction force, medial-lateral and anterior-posterior center of pressure (COP) and tibialis anterior (TA) and gluteus medius (GM) onsets will be shorter with sural stimulation go cue as compared to a visual go cue.

Hypothesis 2: The vertical ground reaction force, speed of force onset, medial-lateral and anterior- posterior COP, and TA /GM EMG of the stepping limb will be enhanced with sural stimulation go cue as compared to a visual go cue.

Aim 2: To compare step initiation APAs of individuals with hemiparesis due to stroke when stepping to visual or sural go cue when stepping with the paretic vs. non-paretic leg.

Hypothesis 3: When stepping with either the paretic or non-paretic leg, the non-paretic leg will provide a greater contribution to COP excursions than the paretic leg.

Hypothesis 4: When stepping with either the paretic or non-paretic leg, the non-paretic leg will demonstrate greater EMG contribution to the APA than the paretic leg.

Aim 3: To describe the relationship, through linear regression, between the degree of asymmetrical standing to the influence of sural stimulation on reaction times and APA generation.

Hypothesis 5: The amount of loading asymmetry will not influence the shortening of reaction times produced by sural stimulation cuing.

Hypothesis 6: As the amount of loading asymmetry decreases, the influence of sural stimulation on loading force, speed of force onset, COP excursions and EMG will lessen.

Chapter 4: Methods

4.1 Subjects

Fifteen subjects were recruited through local stroke support groups, referrals from physical therapy and physical medicine clinics and flyer postings (Appendix A). Inclusion criteria included: 1) male or female > 18 years of age; 2) history of a single stroke $\geq$ 3 months from time of study enrollment (confirmed by imaging dictation report at time of stroke); 3) independent household and/or community ambulation with or without assistive device or ankle-foot orthotic; 4) ability to take 3 steps unassisted without use of the AFO or assistive device; 5) adequate vision to see ready light and

computer monitor (both approximately 6 feet away); 6) ability to feel sural stimulation at non-noxious levels (to be determined with trial stimulation once consented). Exclusion criteria included: 1) receptive or expressive aphasia that impairs ability to understand directions and/or give timely, accurate feedback to researcher; 2) orthopedic disorders that limited ability to take steps; 3) any implanted, active medical device; 4) Botox or Phenol injections to lower extremities within six months of participation; 5) cerebellar, basal ganglia or brainstem stroke.

4.2 Instrumentation

Nerve Stimulation

A Grass S88 electrical stimulator delivered a constant current stimulation through a stimulus isolation unit. The electrical stimulus was applied using a bipolar electrode placed over the most superficial aspect of the sural nerve's pathway – distal to the lateral malleolus and approximately halfway between the malleolus and Achilles tendon. The electrode was secured with tape and a flexible bandage (Coban ®). The sural cue was delivered with a 10ms train of 0.1ms pulses at 300/seconds with an intensity of 1.5 times the radiating threshold.

Electromyography (EMG)

Bipolar Ag bar electrodes (bars were 10mm in length, 1mm in diameter and spaced 10mm apart) with pre-amplification were placed over cleaned skin and collected EMG recordings from bilateral TA and GM muscles. A reference electrode was placed over the right tibial bone in all subjects. Signals were amplified with a Delsys Bagnoli-8

channel EMG system that filtered with a bandwidth between 20Hz and 450 Hz. The common mode rejection for this unit is 92dB. The amplifier gain was set at 10K. The raw EMG was fully rectified within an Excel spreadsheet.

Force Plates

Force plate data were collected using two Bertec Corp (Columbus, OH), model 4060-NC force platforms embedded side by side in a level, custom built platform. The force platform data was streamed to a custom-built Lab View data acquisition and analysis program that sampled each channel at 1000Hz. Each subject was placed in a body harness which was secured to an overhead tract system that allowed for unimpeded stepping responses while simultaneously preventing any unintentional tripping or floor contact.

4.3 Clinical Measurement Tools

Modified Ashworth Score

Spasticity is well known as a velocity-dependent increase in muscle tone encountered during passive movement. It can result from an upper motor neuron injury such as stroke. The prevalence of spasticity in stroke survivors has been reported in amounts ranging from 17% [50] to 38%. [51] The Modified Ashworth Scale (MAS) was developed to improve the sensitivity of the original 5-point Ashworth scale. [52] The modified scale has a 6-point scale ranging from "0" (no increase in muscle tone) to "4" (affected part(s) rigid in flexion or extension) (Appendix B). Intrarater reliability is considered moderate in persons with stroke when assessing lower limb muscles. [53,54]

Spasticity was assessed in eight lower extremity movements; hip (flexion, extension, abduction, adduction), knee (flexion, extension), ankle (dorsiflexion, plantarflexion).

Goniometric Ankle Measurements

Goniometric measurements are routinely used in clinical and research settings to assess ankle joint range of motion (ROM). An accepted standardized positioning for ankle ROM measurements is in the supine position with the knee extended. [55] The center of the fulcrum was aligned over the lateral aspect of the lateral malleoulus, the proximal arm of the goniometer was aligned with the head of the fibula and the distal arm remained parallel to the lateral aspect of the fifth metatarsal. [55] Goniometric measurements of ankle dorsiflexion and plantarflexion are considered reliable and clinically valid measurements with interclass coefficients (ICC) values from .74-.90. [56-58] A universal goniometer with 1º increments was used to measure active ankle ROM in all subjects before stepping trials.

Strength Assessment

Strength was assessed in three major muscle groups of each lower extremity: 1) hip (flexors, extensors, abductors, adductors); 2) knee (flexors and extensors); 3) ankle (dorsiflexors and plantarflexors). Manual muscle testing is a common assessment tool to evaluate muscle strength in both clinical and research settings. Resisted isometric holds in standardized positions were graded on a 0-5 scale.

Sensory Screen

A somatosensory screen is a commonly used clinical tool to assess the integrity of the primary somatosensory system. Sensation was tested distal to the knee in both lower

extremities using a Semmes Weinstein (10g) monofilament over the lower leg dermatomes (L4, L5, S1, S2). A total of 10 trials with the monofilament encompassing the dermatomes were performed on each leg. Impairment in light touch is indicated if the subject was unable to correctly identify when the stimulus was applied at least 65% of the time. [59] With 10 applications of the monofilament to each leg, impairment would be considered present if the subject missed 3-4 on either leg.

Modified Falls Efficacy Scale (mFES)

The Modified Falls Efficacy Scale (mFES) is an expanded version of the original Falls Efficacy Scale [60] and is designed to assess an individual's balance confidence while performing a variety of physical tasks.[61] The modified version added four, more challenging tasks (using public transportation, crossing roads, light gardening, using steps at home) to better reflect the physical challenges of more active, community dwelling elderly (Appendix C). The MFES has been demonstrated to be a reliable and valid measure of falls self-efficacy in older people with balance disturbance. [61] Healthy elderly with no history of fall in the previous 12 months had a mean mFES score of 9.76 (SD = .32) compared to a mean of 7.69 (SD = 2.21) for elderly fallers. Additionally, the mFES scores were more strongly associated to post-stroke activity and participation than physical performance measures of balance, gait speed or walking capacity. [62]

Physical Activity Scale In persons with Disability (PASIPD)

The Physical Activity Scale in Persons with Disability (PASIPD) was created to assess physical activity of individuals with disabilities for use in epidemiologic studies. [63] The instrument is a modification of a previously developed tool, the Physical Activity

Scale for the Elderly (PASE) [64] that has previously shown validity in classifying healthy elderly people by level of daily physical activity. [65,66] The tool queries the number of days a week and daily hours of participation in five distinct categories of physical activity; home repair, lawn and garden work, vigorous and moderate sport recreation and occupational and transportation activities over the past seven days (Appendix D). The tool is scored by multiplying each item by a MET value associated with the intensity of each activity and summing the values of questions 2-13 (item 1 is used for practice). The mathematical maximum score is 199.5 MET hour/day. As an example, an individual who walked or wheeled outside the home 5 - 7 days a week for 2 - 4 hours daily, performed light housework 3 - 4 days a week for 1-2 hours daily, performed heavy housework 1 - 2 days a week for 1-2 hours daily, and worked 5 - 7 days a week for 5-8 hours daily would receive a PASIPD score of 22.74 MET hour/day. [63]

Compared to other indirect physical activity measurement tools, the PASIPD demonstrates similar correlation strength between indirect and direct measures of physical activity. [67-69] Interpretation of PASIPD data is complicated by the overriding reality that individuals are inclined to over-estimate physical activity on a self-report. [70,71]

Mini-Mental State Examination (MMSE)

The Mini-Mental State Examination (MMSE) is widely used to assess cognitive changes or screen for cognitive loss in geriatric individuals with or without identified pathologies. [72,73] The screen includes 11 items that assess several aspects of cognition including orientation, concentration, serial subtractions, memory, and language [73] (Appendix E). An individual may score up to 30 points on the exam. Scores of $\geq$25 are

considered intact/normal; 21-24 mild; 10-20 moderate and ≤ 9 are severely involved. [74] In this study, the MMSE was used to gain insight into each subject's cognitive abilities.

Fugl-Meyer

The Fugl-Meyer is an impairment based tool consisting of five domains of measurement: upper extremity, lower extremity, balancing ability, sensation and range of motion (Appendix F). [75] The lower extremity motor performance portion is rated on a three point ordinal scale (2 points for full performance, 1 point for partial performance, 0 points for inability to perform). This portion contains elements of reflex activity, volitional movement, and coordination and speed of movement. The lower extremity motor function portion of the assessment has a maximum score of 34. [75] Scores of the lower extremity motor section of the Fugl-Meyer have been positively correlated to walking and upright stability performance in stroke survivors. [76] Furthermore, higher Fugl-Meyer motor subscale scores indicated better performance in gait measures (velocity, cadence, stride length) and balance (upright stability platform measures).

4.4 Study Procedures

Consent

Interested individuals were screened for the inclusion and exclusion criteria over the phone using a prescribed questionnaire (Appendix G). If eligible, the individual provided written consent to acquire imaging records of the individual's stroke. All subjects completed an informed consent (Appendix H) approved by the Institutional Review Board at the University of Minnesota and a Health Insurance Portability and Accountability Act (HIPAA) before beginning the experiment (Appendix I).

Data Protection

Any records containing protected health information, signatures or identifying details were maintained within a lock cabinet inside a locked office. One document with subject contact information and coding key identifying their subject number was maintained on a private, password protected computer.

Physical Examination

The physical examination was conducted after the stepping trials to minimize fatigue. The examination included manual muscle testing of the lower extremities, goniometric measurements of bilateral ankle range of motion, modified Ashworth assessment, sensory screen of bilateral distal lower leg and foot, Fugl-Meyer lower extremity motor assessment, MMSE, mFES, and the PASIPD. All clinical assessment scores and demographic information was recorded on a data collection form (Appendix J).

Electrode Set-Up and Stimulation Trial

The subject's skin was cleansed with an alcohol swab in preparation for electrode placement. Tibialis anterior recording electrodes were positioned midpoint between the lateral malleolus and the fibular head, over the belly of the muscle. Gluteus medius electrodes were positioned midway between the iliac crest and greater trochanter of the femur. Electrode placement was confirmed by the myoelectric signal during active dorsiflexion (TA) and active hip abduction (GM).

The subject stood to determine the radiating threshold for sural stimulation. Stimulus intensity was adjusted slowly until the subject reported the first focal sensation

near the electrode. Once perception of stimulus was confirmed, the intensity was slowly increased until the subject felt the stimulus radiating beyond the initial focal location. The intensity was decreased back to only a focal stimulus and then returned a second time to the point of the radiating sensation. The radiating threshold (RT) was determined from the second reading and was considered to be the lowest stimulation intensity at which there were clear radiating paresthesias into the area of skin innervated by the sural nerve. The subject's 1.5 RT (1.5 times his/her RT) was determined and set for the duration of the first 30 stepping trials for a given leg. Before the stepping trials, the subject received a single stimulus at 1.5 RT to familiarize him/her with the sensation of the sural nerve go cue used during the stepping trials. All subjects confirmed feeling the stimulus but denied that is was painful or noxious. This procedure was repeated on the opposite leg before the second set of 30 stepping trials.

Stance Position

Each subject was asked to stand comfortably with one foot on each force plate. Loading symmetry of his/her stance was not controlled. However, once a position was established, an outline of each foot was traced on the force plate. The subject was asked to stand within the tracings before each stepping trial for all 60 stepping trials.

Practice Trials

The subject was placed in the harness and secured to the overhead suspension system. The subject was given practice stepping trials on the force platform with each go cue (sural and visual) to get accustomed to the experimental task. Practice trials ended when the subject demonstrated and verbalized an understanding of the stepping task. Practice trials ranged from 3-5 steps for each leg.

Stepping Trials

All subjects completed at least 15 stepping trials for each go cue on each limb. The initial stepping limb was determined randomly for the first subject and then subsequently alternated for subsequent subjects. The same randomized order of cue (sural or visual) presentation was used for each subject. Five catch trials were randomly presented during each stepping limb series. The catch trials consisted of giving the subject a ready cue without a go cue presentation. The purpose of the catch trials was to ensure that the subject stayed focused on reacting to the go cue rather than anticipating and generating steps prematurely. The instructions were to "step as fast and as far as you can when you receive the go cue". Stepping trials were repeated if the subject initiated the step with the wrong limb, moved before the go cue or had a misstep of any kind. The stepping series was complete when 30 good (based on visual inspection of the subject's performance) steps were recorded. Each subject was given a seated rest of 5-10 minutes while the stimulator electrode was placed on the contralateral leg.

Chapter 5: Data Analysis

Ground Reaction Force (GRF)

Three dependent variables were analyzed: 1) loading reaction time; 2) loading amount; 3) speed of loading/unloading. Each variable was analyzed under all conditions of limb (paretic vs. non-paretic and stepping vs. stance), cue (sural vs. visual) and action (stepping or standing). All force data were normalized to percent body weight (%BW) for across subject comparisons.

5.1 Loading Reaction Time

Loading and unloading reaction times (Fz RT) were determined using the filter function of the Excel program and were defined as the time between the "go" cue and the time when the vertical force changes were greater than three standard deviations from the baseline. Loading occurred on the swing limb while simultaneous unloading occurred on the impending stance limb (Fig. 1). Loading reaction times were expressed in milliseconds.

5.2 Loading Amount

Loading amount (% BW > Baseline) was calculated using an interactive excel spreadsheet and was defined as the amount of force achieved above the baseline between the stimulus and the peak Fz (Fig. 1). Force values were normalized and expressed as a percent body weight change from baseline according to the formula:

Normalized Fz = (Peak Fz- Baseline Fz/Body Weight) * 100

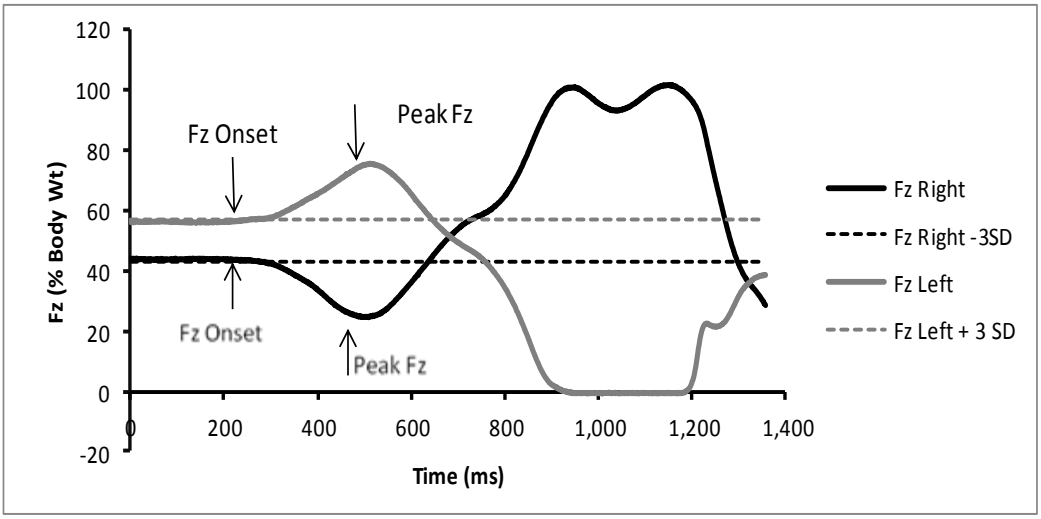


Figure 1: Loading and unloading forces (Fz) for a left step. Go cue occurs at t = 0. Reaction times determined from go cue to where Fz crossed baseline Fz +/- 3 SD. Peak Fz minus mean baseline Fz was used to calculate peak loading amount.

5.3 Loading Speed

The peak speed was determined by taking the time derivative of the loading force from load onset to peak load (Fig. 2). All loading speeds were expressed as % BW/s.

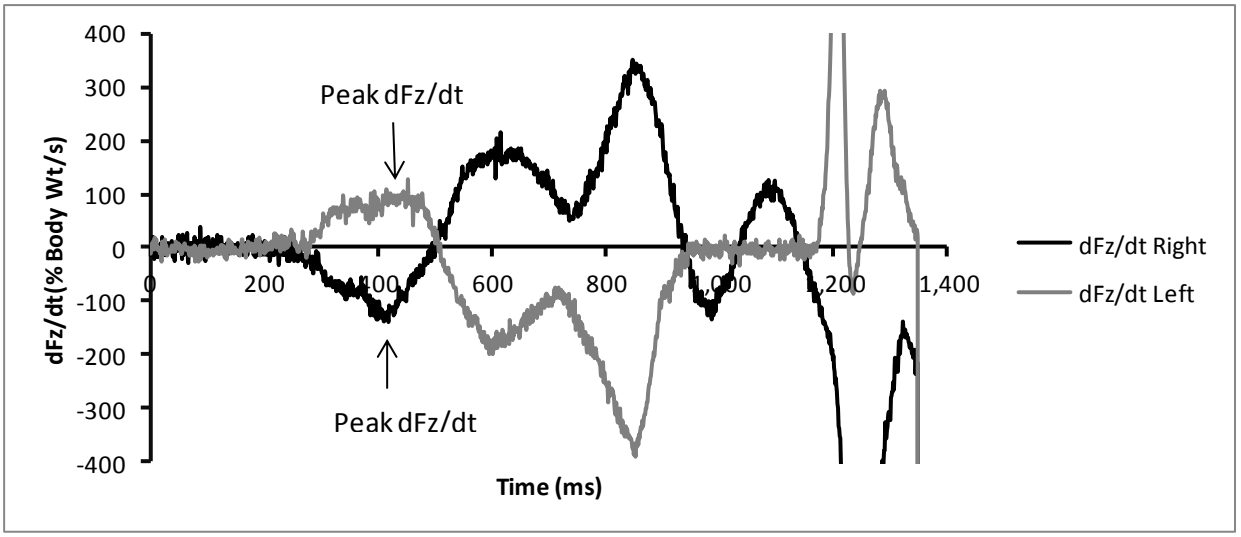


Figure 2: Time derivative of Fz loading and unloading forces for a left step. Same data as in Figure 1. Peak dFz/dt's determined using Excel MAX or MIN function for time interval up to first crossing of the two dFz/dt traces.

Center of Pressure (COP)

Three dependent variables were measured in the COP analysis: 1) Net COP movement in the anterior-posterior (Yp) and medial-lateral direction (Xp); 2) Net COP reaction time in the anterior-posterior and medial-lateral direction; 3) Overall change in individual limb moments (Mx and My) . The Net COP reaction times and excursions and the change in moments were analyzed under conditions of limb (paretic and non-paretic) and cue (sural and visual).

5.4 COP Reaction Time

The COP reaction times (onset of COP movement) were calculated for both Net Xp and Net Yp using an interactive Excel spreadsheet and were defined as the time between the stimulus and the time when the movement changes were greater than three standard deviations from the baseline (Fig. 3 A & B). Onset times were expressed in milliseconds.

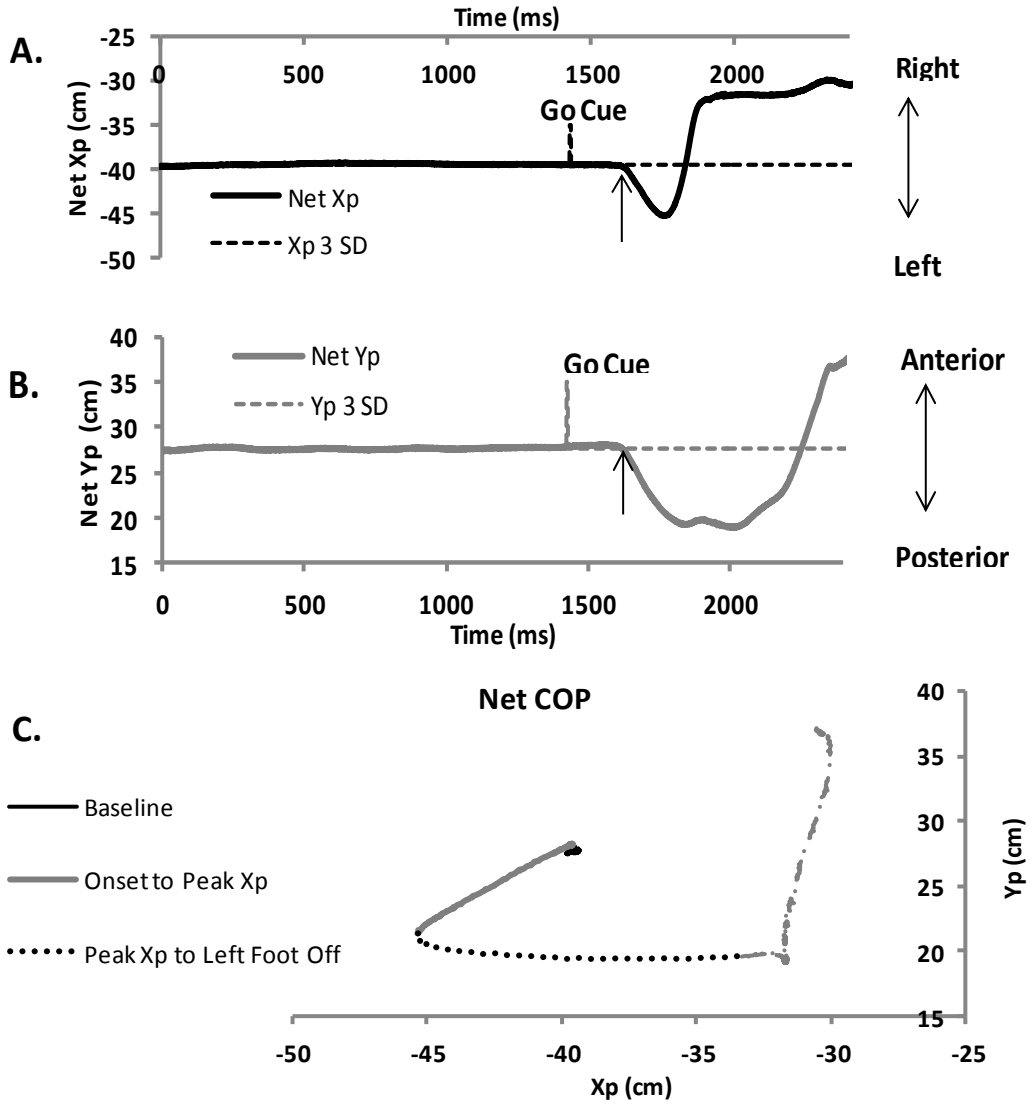


Figure 3: Net COP displacements in (A) medial-lateral, Xp and (B) anterior-posterior, Yp directions. Reaction times determined from go cue to when COP increased or decreased 3 SD beyond baseline levels (arrows in both figures). C: Net COP changes for a left step. COP initially moves posterior and laterally towards the left stepping limb, then is shifted to the right limb and anterior.

5.5 Medial-Lateral and Anterior-Posterior Net COP Excursion

The COP in the medial-lateral and anterior-posterior direction were assessed both individually (paretic and non-paretic limbs) and used collectively to calculate net COP. The analysis timeframe was between the stimulus onset, up to stepping limb foot-off (Figure 3 C). The calculation of the COP using the moments in the medial-lateral and anterior-posterior was as follows:

Xp = -My/Fz x100 (where Xp is medial-lateral COP in cm, My is anterior-posterior moment, Fz is vertical loading)

Yp = Mx/Fz x100 (where Yp is anterior-posterior COP in cm, Mx is medial-lateral moment).

For this study, only Net COP was analyzed and was calculated as follows ("r" and "l" refer to right and left limb):

$$\textbf{Net Xp} = Xp_{(r)} * \left(Fz_{(r)}/Fz_{(r)}+Fz_{(l)}\right) + Xp_{(l)} * \left((Fz_{(l)}/Fz_{(r)}+Fz_{(l)}\right)$$

$$\textbf{Net Yp} = Yp_{(r)} * \left(Fz_{(r)}/Fz_{(r)}+Fz_{(l)}\right) + Yp_{(l)} * \left(Fz_{(l)}/Fz_{(r)}+Fz_{(l)}\right)$$

To compare across subjects, the COP values were normalized to the each subject's foot size. Both feet were traced onto paper; a line was drawn between the tip of the great toe and the lowest aspect of the heel. At 15% of the anterior-posterior line, a bisecting line was drawn in the medial-lateral direction to represent the foot width. An average foot width and length was calculated from the bisecting lines and used to calculate medial-lateral and anterior-posterior net COP displacements respectively. Net COP changes were expressed as a percent excursion of either foot width (Xp) or foot

length (Yp). Figure 4 depicts the bisecting lines drawn on the foot tracing that were used to normalize COP displacements.

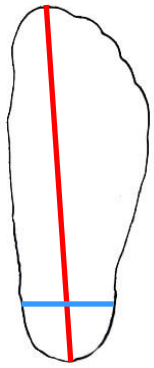


Figure 4: Sample foot tracing showing anterior-posterior line (tip of great toe to lowest aspect of the heel) and the medial-lateral bisecting line (perpendicular line at 15% of anterior-posterior line). Net COP displacements were expressed as a percentage of movement of foot length (Yp) or foot width (Xp).

5.6 Moments

Moments contributing to the medial-lateral (My) and anterior-posterior (Mx) COP movements were analyzed to examine inter-limb contributions towards the net COP (Figure 5 A & B). From the raw data, the change in each moment under each limb was calculated by subtracting the average baseline value from the peak moment. Therefore, each moment (My and Mx) had a paretic limb and non-paretic limb contribution – or an amount of change under each limb contributing to the net COP. The change in moments was normalized to body weight for comparison across subjects. Calculations for the moments were as follows:

My peak – My baseline average = Δ My (paretic limb and non-paretic limb)

Mx peak – Mx baseline average = Δ Mx (paretic limb and non-paretic limb)

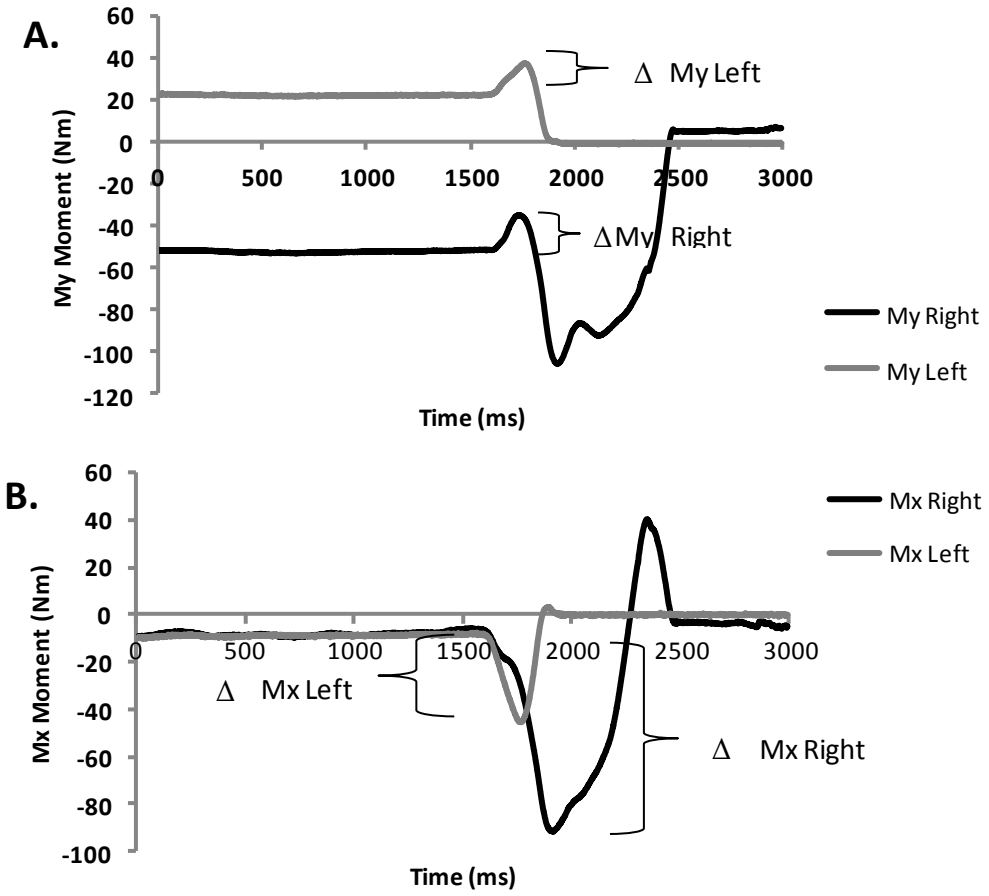


Figure 5: Moments in the (A) anterior-posterior, My and (B) medial-lateral, Mx directions. Inter- limb contribution to net COP displacements was made by comparing ΔMy (right to left) and ΔMx (right to left).

Electromyography (EMG)

Three dependent variables of EMG data were analyzed: 1) TA onset (paretic and non-paretic limb); 2) GM onset (stepping limb only); 3) Amount of TA and GM activity. Both the onset and the amount of EMG were determined by using a cumulative sum (CUSUM) technique. The CUSUM was constructed by first determining a mean baseline period of EMG (typically 300-400ms before step initiation onset), sequentially

subtracting this mean from each individual data period and then summing the differences. Increases from the mean were indicated by a positive slope and decreases from the mean were indicated by a negative slope (Fig. 6).

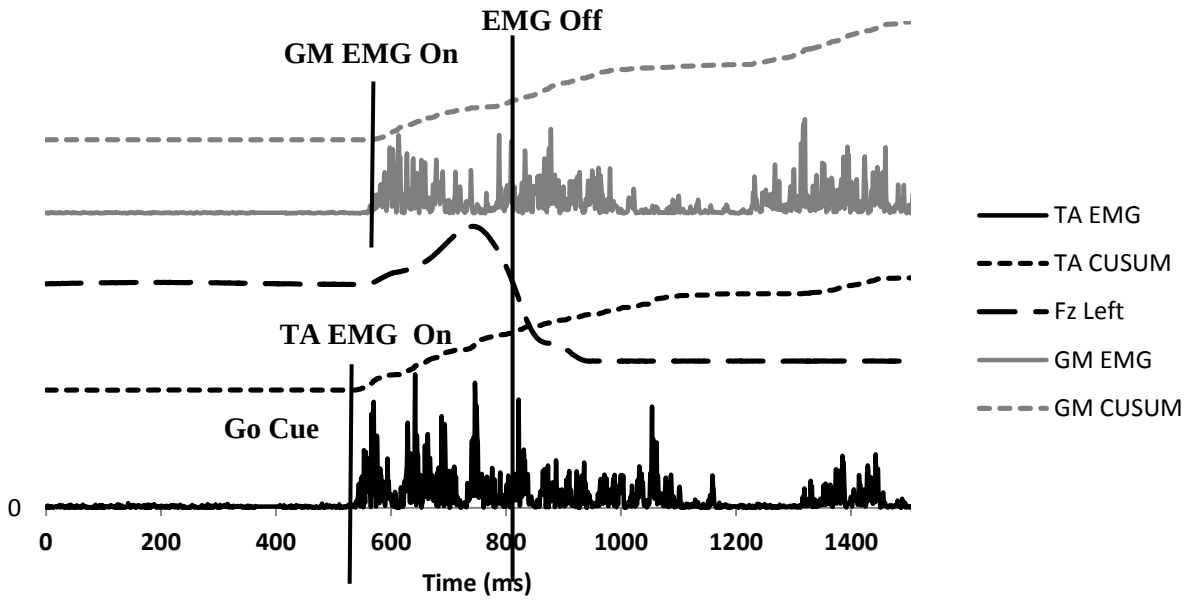


Figure 6: TA and GM EMG. Reaction times determined from go cue to when CUSUM exceeded the baseline by 3 SD. Offset when Fz loading force crosses baseline (see rationale on pg. 33-34). CUSUM determined amount of EMG activity within defined APA.

5.7 TA and GM Reaction Times

Onset times were calculated using the CUSUM curve and the filter function in an Excel spreadsheet. Reaction time of both muscles was defined as the time between the go cue and the time at which the CUSUM exceeded the baseline by at least three standard deviations (Fig. 6). These reaction times were expressed in milliseconds.

5.8 TA and GM EMG

TA EMG was recorded bilaterally and analyzed under all conditions of cue (sural and visual), limb (paretic and non-paretic) and action (stepping and standing). GM EMG was analyzed on the stepping limb only under conditions of cue (sural and visual) and limb (paretic and non-paretic). The amount of EMG was calculated as the average EMG under the CUSUM curve between onset and the time that Fz decreased past the baseline loading. This endpoint was chosen as a conservative measure to ensure that EMG activity (particularly TA) in preparation for toe-off would not be included in the EMG analysis of the APA. Figure 7 illustrates an example from one subject and highlights the rationale for the EMG analysis cut-off point. Two EMG burst are seen to occur, the first coincided with the loading onset and the second, during the late part of the unloading. We associate the first EMG burst with the APA and the second burst with the ensuing toe off of the stepping limb. In many other records, however, discriminating between the two bursts was difficult. To ensure that the toe off burst of EMG was not included in the measurement of the APA activity, we chose the time at which the loading force (Fz) decreased below the baseline Fz as the cutoff for EMG analysis for the APA.

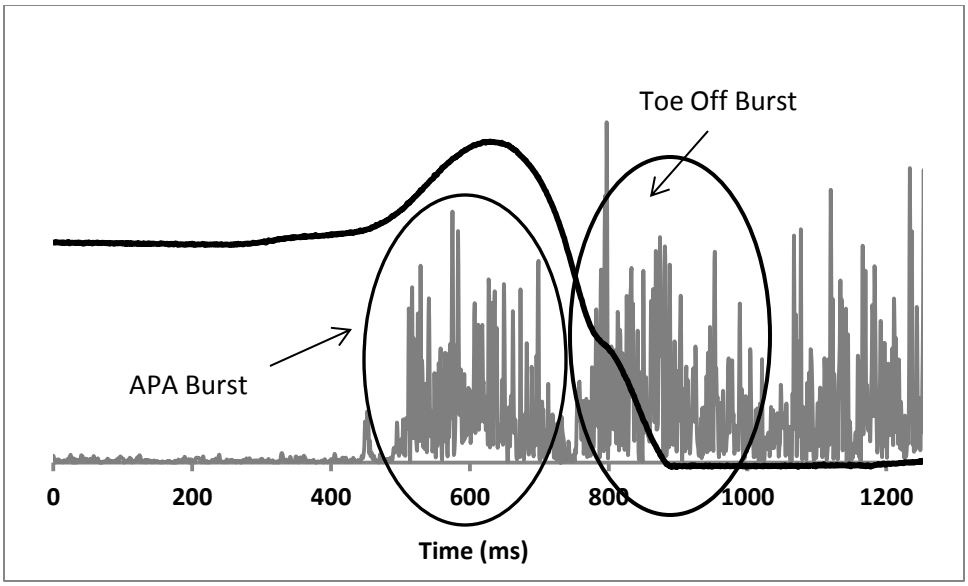


Figure 7: TA bursts during APA and in preparation for toe off. First burst associated with TA APA activity; second burst associated with stepping limb toe off.

EMG was normalized to the average EMG for the visual cue stepping condition. For the paretic stepping limb, each trial for both visual and sural cue was normalized to the average EMG of all visual cue trials. Similarly, the non-paretic TA was normalized to the non-paretic limb stepping with the visual cue. Because the GM EMG was analyzed only on the stepping limb, it was normalized to the GM activity on the stepping side with the visual cue. This normalization procedure forced the visual cue average to 100% and the sural cue average to be either greater than or less than the visual cue values.

Baseline Loading – Symmetry

Inter-limb loading was assessed by taking the average vertical load under each limb (paretic and non-paretic) over a baseline period prior to any ready or go cue. Baseline loading was normalized and expressed as a percent of body weight. The

average baseline loading measurement was used to assess the relationship between standing symmetry (or asymmetry) and the dependent variables.

Chapter 6: Results

A total of 15 subjects completed the experimental protocol. The subjects' demographics are summarized in Table 1. A detailed description of each subject can be found in Appendix K. The subjects' impairment-based clinical measurements are summarized in Tables 2 and 3. A detailed description of each subjects' impairments measurements can be found in Appendix L.

Table 1: Baseline characteristics of the participants (n=15)

Characteristics	Value
Gender (male/female)	9/6
Side of hemiparesis (right/left)	5/10
Age, median years (range)	60 (35-84)
Time after stroke, median years (range)	7 (1-20)
MMSE, mean score (SD)*	27 (4)
Fugl-Meyer LE motor, mean score (SD)**	28 (5)
PASIPD, median score (range)	15 (.7 - 40)
MFES, mean score (SD)†	9

* Max score = 30, ** Max score = 34, †Max score = 10

Table 2: median MAS and MMT scores for all subjects

	MAS		MMT	
Movement	P	NP	P	NP
Hip Flexion	0 (0-2)	0	4 (2-5)	4+ (3-5)
Hip Extension	0 (0-2)	0	3+ (2-5)	4+ (4-5)
Hip Adduction	0 (0-3)	0	3 (2-4)	4 (3-5)
Hip Abduction	0 (0-3)	0	3+ (2-4)	5 (4-5)
Knee Flexion	0 (0-3)	0	3+ (2-4)	5 (4-5)
Knee Extension	1 (0-4)	0	5 (4-5)	5 (4-5)
Ankle Dorsiflexion	0.5 (0-3)	0	3 (0-5)	5 (4-5)
Ankle Plantarflexion	0.5 (0-3)	0	3 (1-5)	5 (3-5)

MAS = modified Ashworth Scale; P = paretic limb; NP = non-paretic limb; value in ( ) = range

Table 3: median ROM and sensory testing scores

	P	NP
AROM DF	-3° (-25° to 15°)	5° (-18° to 25°)
AROM PF	41° (5° to 50°)	45° (35° to 50°)
Sensation †	9 (7-10)	10 (9-10)

† = out of 10 trials

Data Inspection

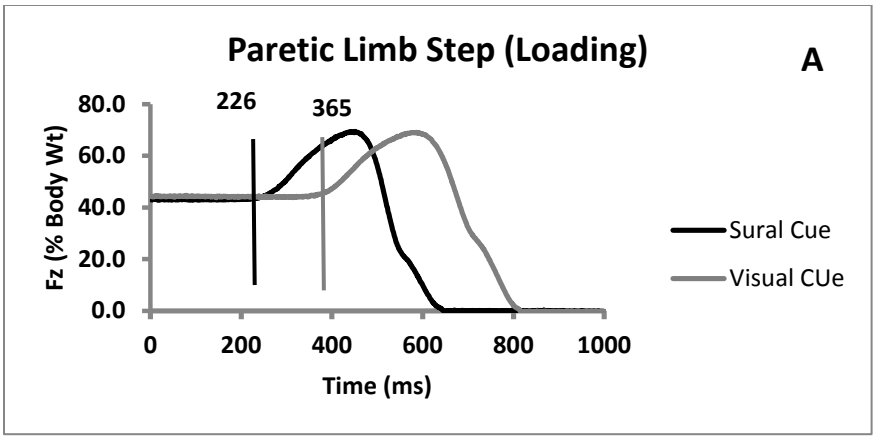
Data were inspected on several levels. Each subject took 30 steps with the paretic limb and 30 steps with the non-paretic limb. Of those 30 steps up to twelve good stepping trials for each limb were selected for further analysis – for a total of a possible 48 stepping trials per subject. The median number of qualifying trials was 47 with a range of 36-48. One subject had 36 trials accepted due to highly unstable baseline loading, otherwise subjects ranged from 40-48. Trials were eliminated due to highly unsteady baselines, incorrect stepping limb, or other abnormalities apparent only after visual inspection.

The next level of analysis occurred within the individual stepping trials. Individual data points (i.e. Fz RT) were eliminated if the value was greater than three standard deviations above the mean for a given measurement. In the force plate data (Fz RT, speed of loading, peak loading), deleted data accounted for approximately 1.3% of the total data points for those variables. For the COP data (Net Xp and Yp, onset of Xp and Yp), approximately 2.9% of the data were eliminated due to values greater than three standard deviations from the mean. The EMG had the greatest loss with approximately 25% of the data being eliminated due to quality, temporal or analysis inadequacies.

Ground Reaction Force (GRF)

6.1 Loading Reaction Time

The effects of cueing (sural or visual), stepping limb (paretic and non-paretic) and action (loading and unloading) on the Fz RT were analyzed with an additive three-way analysis of variance (ANOVA) model. The Fz reaction time was significantly faster when given the sural go cue compared to the visual cue ($p < .0001$) Figure 8 is a representative example of this result and depicts Fz onsets of 139 ms and 132 ms earlier for sural versus visual cueing for loading and unloading responses respectively.



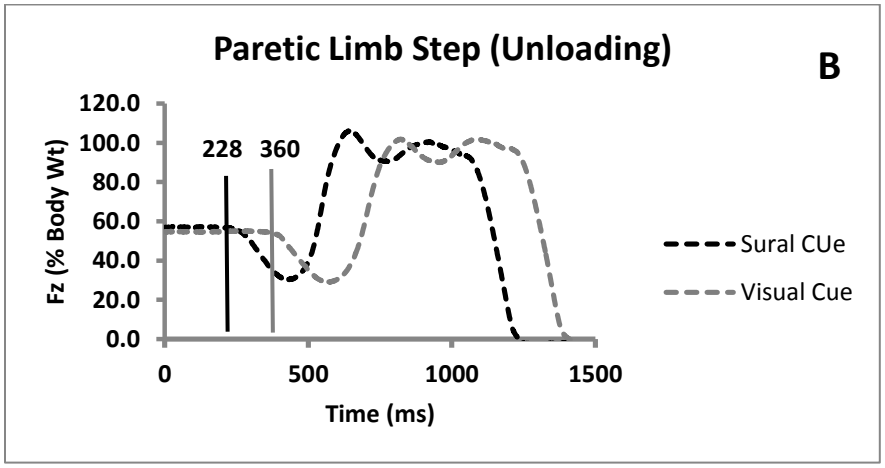
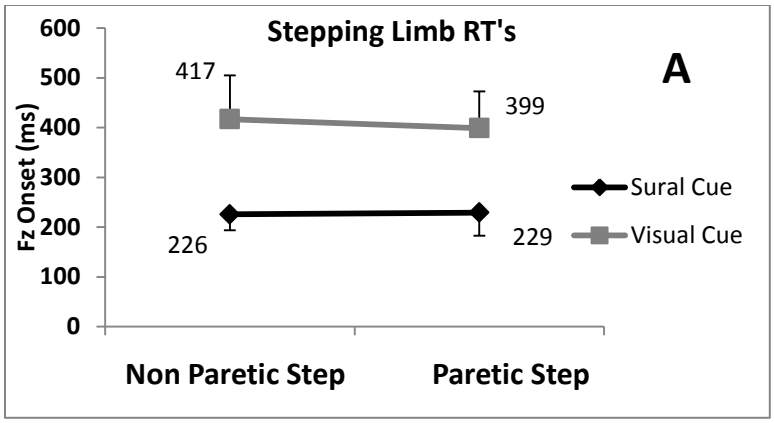


Figure 8: Representative example of Fz reaction time on paretic limb for sural cue compared to visual cue. Go cue is at time = 0. A) Fz loading RT. B) Fz unloading RT.

From the ANOVA model , the estimated Fz RT for the sural go cue was 181 ms faster than for the visual cue with a 95% confidence interval (CI) (158 ms , 204 ms). Pooled data for stepping and stance limb Fz reaction times are depicted in Figure 9 (A & B).



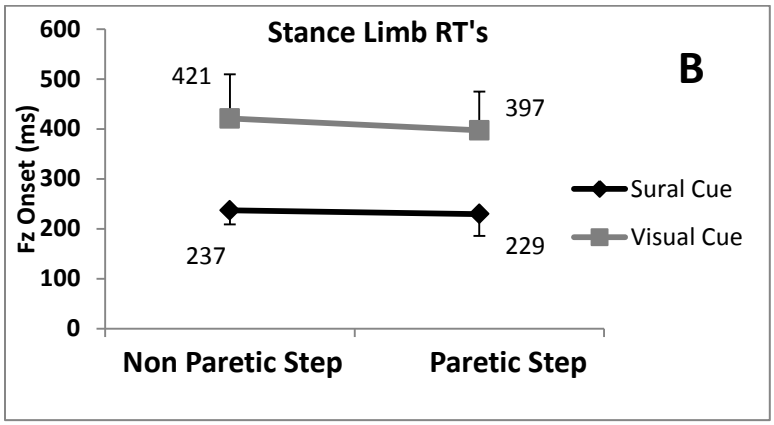


Figure 9: Pooled mean Fz onset data for paretic and non-paretic step for measurements taken on the; (A) stepping side and (B) stance side. Numbers within graphs represent mean onset times for each specific condition.

6.2 Loading Amount

The effects of the cueing and stepping limb (paretic or non-paretic) on Fz loading amounts were analyzed with a two-way ANOVA model. Because of the general symmetry between loading and unloading forces, statistical analysis was confined to loading responses. Although loading forces were generally larger for sural versus visual

cueing (Fig. 10), the differences were not statistically significant (p = 0.3622). There was a significant difference in the loading amount between the paretic stepping limb and non-paretic stepping limb (p-value = 0.0308). The paretic stepping limb loaded an estimated 5% BW more compared to the non-paretic stepping limb with a 95% CI (.45% BW, 9.1% BW).

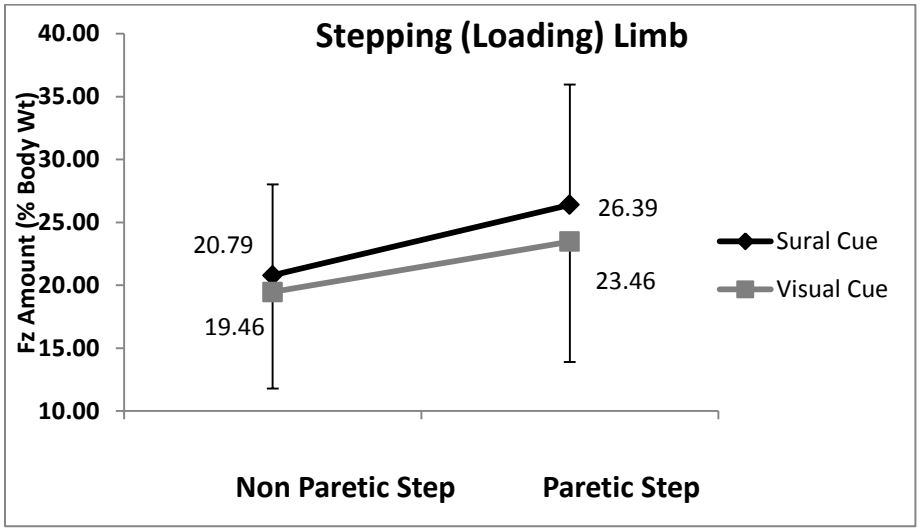


Figure10: Pooled mean data for Fz loading amount on stepping (loading) limb. Loading amounts significantly more with paretic limb stepping compared to non-paretic limb stepping; estimated 5% BW/s more with paretic step.

6.3 Loading Speed

6.3.1 Cue (Visual or Sural) and Stepping Limb (Paretic or Non-Paretic) Effects

The effects of cueing (sural and visual) and stepping limb (paretic and non-paretic) on the speed of Fz loading were analyzed with a two-way ANOVA model. The speed of Fz loading was found to be significantly faster when stepping with a sural cue (p = 0.0417) compared to stepping with a visual cue. Figure 11 depicts a representative

example of the effect in which sural cueing produced a 95% BW/s greater speed than visual cueing. On average, the estimated speed of Fz loading was 44% BW/s faster with the sural cue compared to the visual cue with the 95% CI (1.7% BW/s, 86.7% BW/s) (Fig. 12).

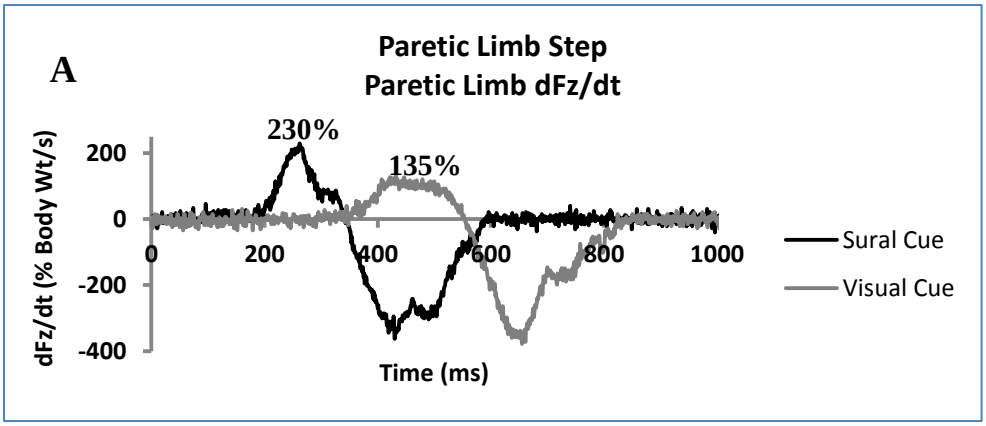


Figure 11: Representative example of Fz loading speed for paretic limb stepping. Sural cue produced significantly faster loading compare to visual cue; estimated 44% BW/s faster loading with sural cue.

The speed of Fz loading was also significantly faster with the paretic stepping limb (p-value = 0.0225) (Fig.12). The paretic stepping limb loaded an estimated 50% BW/s faster compared to the non-paretic stepping limb with a 95% CI (7.2% BW/s, 92.2% BW/s) (Fig. 12)

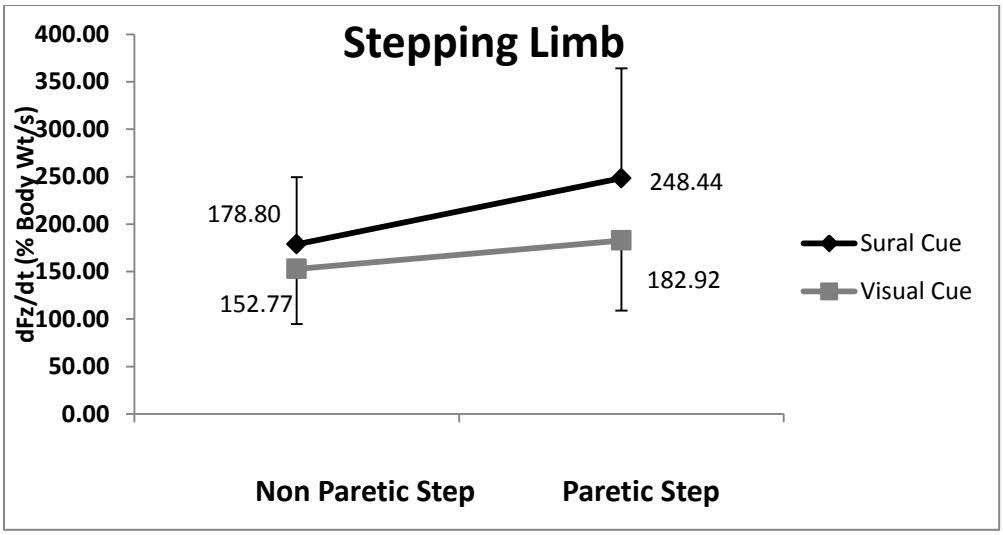


Figure 12: Pooled dFz/dt mean data showing (1) Paretic limb loads significantly faster compared to non-paretic limb; estimated 50% BW/s faster on paretic limb. (2) Sural cue significantly faster loading; estimated 44% BW/s faster with sural cue.

Similarly, the effects of cueing (sural or visual) and stepping limb (paretic and non-paretic) on the speed of Fz unloading were analyzed with a two-way ANOVA model. The difference in the speed of Fz unloading between the sural and visual cue was marginally significant ($p = 0.0804$)(Fig. 13). The speed of Fz unloading was significantly faster on the paretic stepping limb than the non-paretic stepping limb ($p = 0.0142$). From the model, the estimated speed of Fz unloading was 58% BW/s faster with the paretic stepping limb compared to the non-paretic stepping limb with 95% CI (12%, 103%).

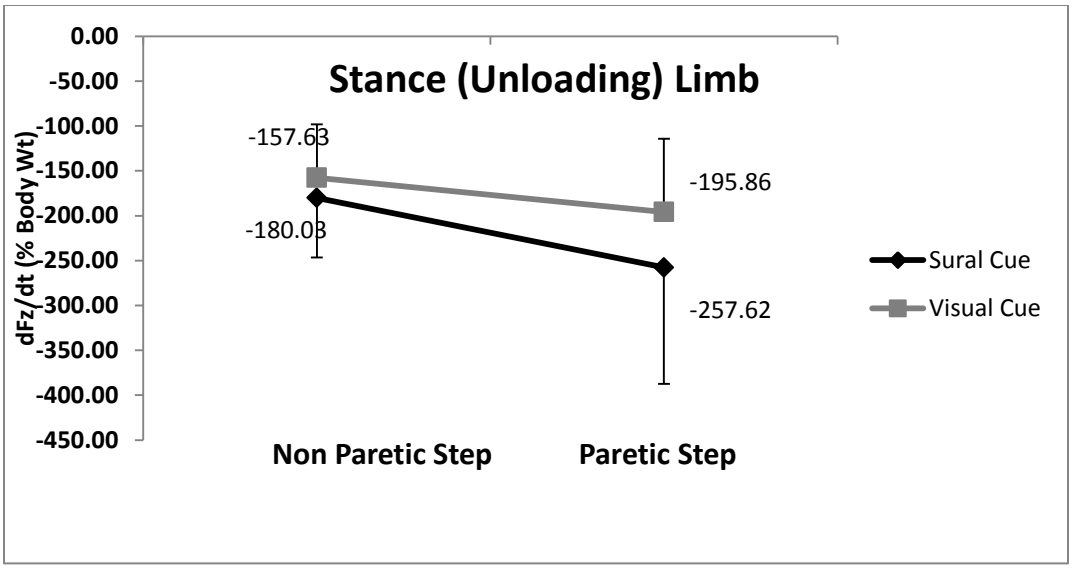


Figure 13: Pooled dFz/dt mean data showing paretic limb unloads significantly faster compared to non-paretic limb; estimated 58% BW/s faster unloading on paretic limb. Speed of unloading approaches significance with sural cue compared to visual cue.

6.3.2 Cue (Visual or Sural) and Limb Action (Loading or Unloading) Effects

The action effects (limb loading and unloading) and cue effects on the speed of Fz for the paretic limb were analyzed with a two-way ANOVA model. In that loading and unloading speeds were of different signs (positive for loading and negative for unloading), all unloading speeds were converted to the absolute value before analysis. Although sural cueing for paretic limb stepping produced faster speeds than visual cueing (Fig. 14 A), the overall effect was just less than significant ($p = 0.0519$). According to the model, the Fz speed on the paretic limb was significantly faster when the limb was loading compared to when it was unloading (p-value = 0.0316). The estimated speed was 47% BW/s faster with paretic limb loading compared to unloading with 95% CI (4.2% BW/s, 88.8% BW/s).

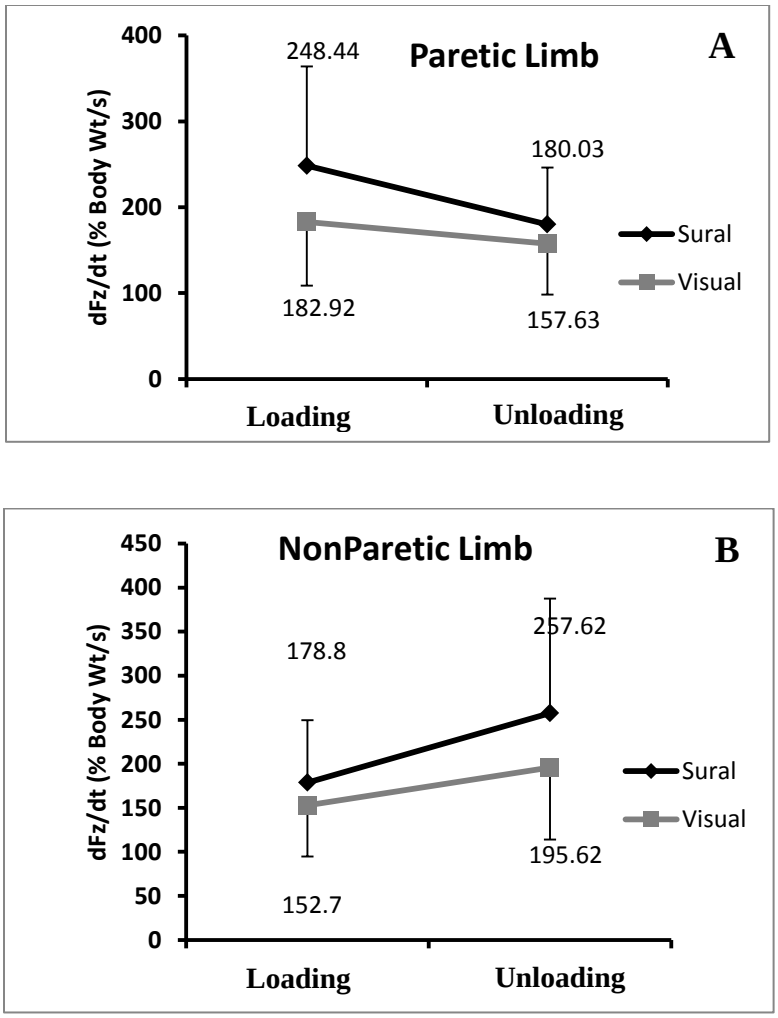


Figure 14: Pooled mean data for cue and limb action effects. (A) Paretic limb data show sural cue faster than visual cue but not statistically significant. Paretic limb loading significantly faster than paretic limb unloading; estimated 47% BW/s faster when loading. (B) Non-paretic limb data shows sural faster loading than visual but not statistically significant. Non-paretic limb unloading significantly faster than non-paretic limb loading; estimated61% BW/s faster when unloading.

Similarly, the action effects (limb loading and unloading) and cue effects on the speed of Fz for the non-paretic limb were analyzed with a two-way ANOVA model. Again, sural cueing produced faster speeds than visual cueing (Fig. 14 B) which were marginally significant ($p = 0.0633$). The Fz speed on the non-paretic limb was significantly faster when the limb was unloading compared to when it was loading ($p = 0.0102$). The estimated speed was 61% BW/s faster when the paretic limb was unloading

compared to when it was loading with a 95% CI (15.0%BW/s, 106.8%BW/s). The speed of Fz on the non-paretic limb was marginally significant with the sural cue compared to the visual cue (p = 0.0663).

Table 4: Loading Speed Results Summary

Loading Speed	Paretic > NonParetic (p = 0.0225)*	Sural > Visual (p = 0.0417)*
Unloading Speed	Paretic > NonParetic (p = 0.0142)*	Sural = Visual (p = 0.0804)
Paretic Limb Speed	Loading > Unloading (p = 0.0316)*	Sural = Visual (p = 0.0519)
NonParetic Limb Speed	Unloading > Loading (p = 0.0102)*	Sural = Visual (p = 0.0663)

*statistical significance

Center of Pressure (COP)

6.4 Xp and Yp Reaction Time

The effects of cueing and stepping limb (paretic or non-paretic) on the net Xp reaction time were analyzed with a two-way ANOVA model. Figure 15(A) depicts a representative example showing statistically significant reaction time for sural cueing versus visual cueing. According to the model, net Xp reaction time was significantly (p < 0.0001) faster with the sural cue compared to the visual cue. The estimated net Xp reaction time was 175ms faster with the sural cue than for the visual cue with a 95% CI (141ms, 208ms)(Fig. 16). The difference in the reaction time was not statistically significantly different for the paretic and non-paretic stepping limb (p = 0.4672).

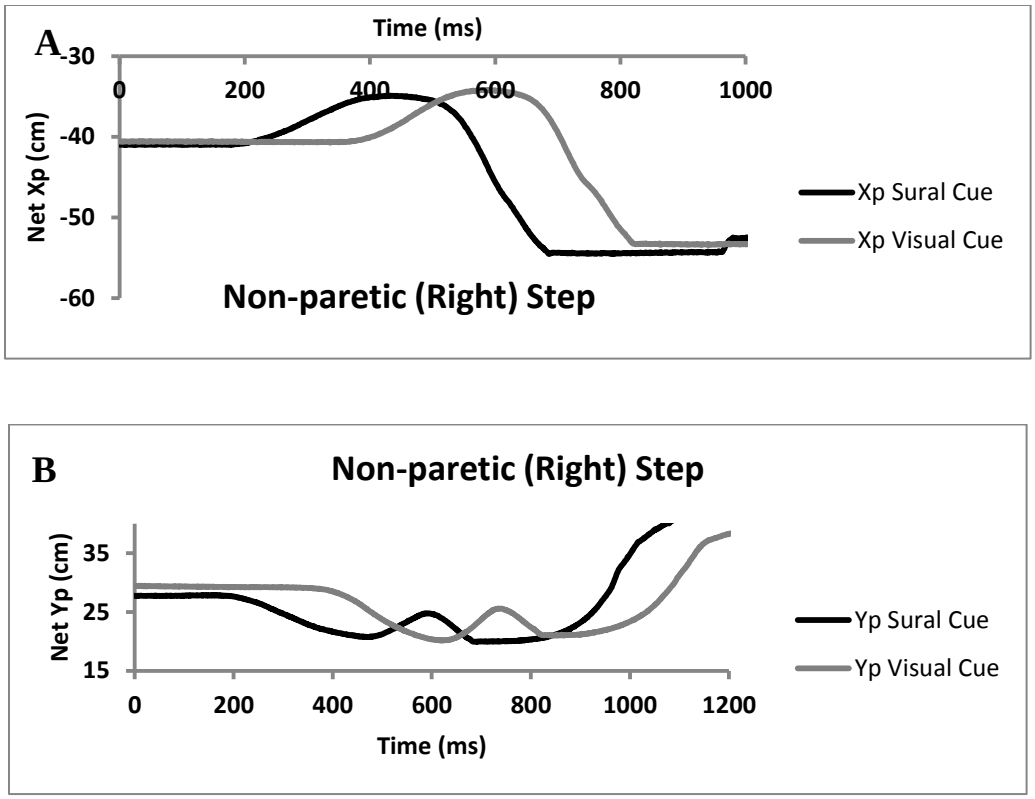


Figure 15: Representative example of net Xp and Yp reaction times showing significantly faster onsets with sural cue. (A) Net Xp; estimated 175ms faster RT with sural cue. (B) Net Yp; estimated 169ms faster RT with sural cue.

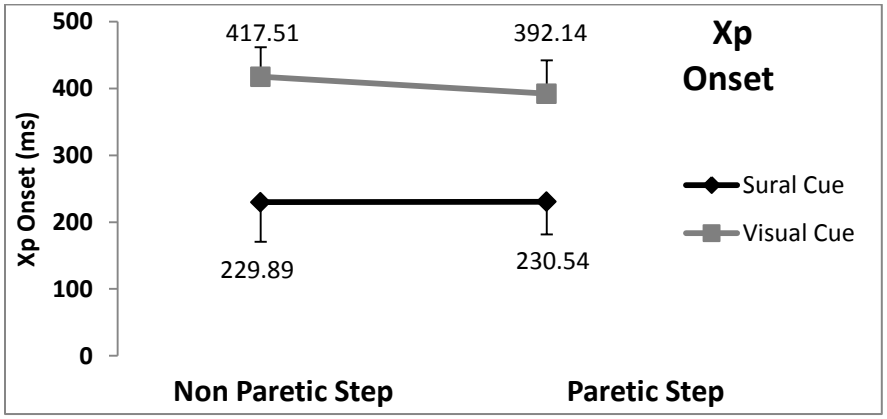


Figure 16: Pooled mean data of Xp onset showing sural cue producing significantly faster reaction times compared to visual; estimated Xp reaction time was 175ms faster with sural compared to visual cue. No significant difference in Xp reaction time with a paretic or non-paretic step.

The effects of cueing and stepping limb (paretic or non-paretic) on the net Yp reaction time were analyzed with a two-way ANOVA model. A representative example of earlier Yp onset with sural cueing is presented in Figure 15 (B). The net Yp reaction time was significantly ($p < 0.0001$) faster with the sural cue compared to the visual cue. The estimated net Yp reaction time was 169ms faster with the sural cue compared to the visual cue with a 95% CI (131ms, 205ms). The difference in the net Yp reaction time was not statistically significantly different for the paretic and non-paretic stepping limb ($p = 0.9447$) (Fig. 17).

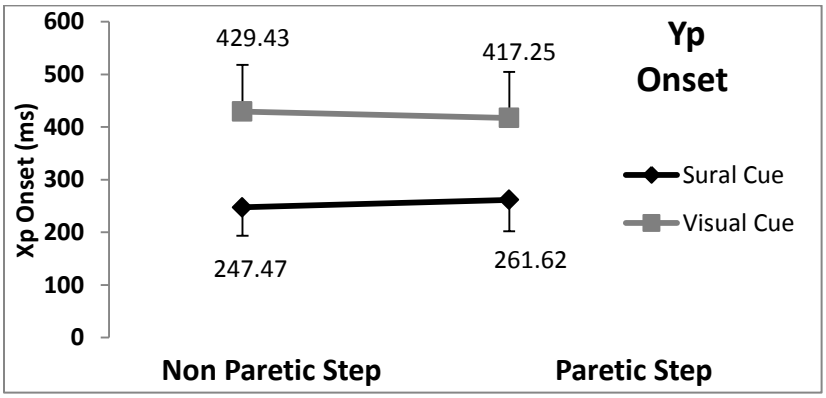


Figure 17: Pooled mean data of Yp onset showing sural cue producing significantly faster reaction times compared to visual; estimated Yp reaction time was 169ms faster with sural compared to visual. No significant difference in Yp reaction time with a paretic or non-paretic step.

6.5 Net Xp and Yp Displacements

The effects of cueing and stepping limb (paretic and non-paretic) on the maximum net Xp when the subject was stepping were analyzed with a two-way ANOVA model. The maximum net Xp was significantly ($p = 0.04$) greater when the subject was stepping with their paretic limb compared to stepping with the non-paretic limb. Figure

18 is a representative example of greater (nearly 3x) Xp displacement with the paretic limb stepping compared to the non-paretic limb stepping. The estimated maximum net Xp was 18% of average foot width more when stepping with the paretic limb compared to stepping with the non-paretic limb with a 95% CI (.36%, 75%). Although sural cueing produced greater Xp displacements difference in the maximum net Xp was not statistically significant ($p = 0.2539$). Figure 19 shows both cueing and limb action results for Xp displacement.

The effects of cueing and limb (paretic and non-paretic) on the maximum net Yp when the subject was stepping were analyzed with a two-way ANOVA model. There was not a statistically significant difference in the maximum net Yp given the sural or visual cue ($p = 0.8081$) or whether the subject was stepping with the paretic or stepping with the non-paretic limb ($p = 0.7892$). Figure 20 depicts pooled data for Yp displacement.

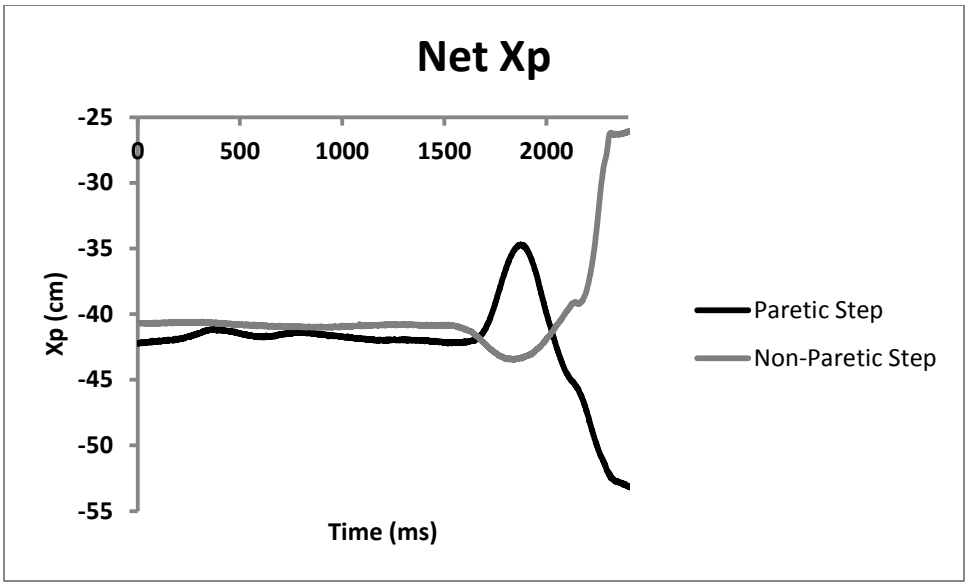


Figure 18: Next Xp displacement greater with paretic step (right limb) compared to non-paretic step (left limb). Both lines represent Xp displacement (medial-lateral). For paretic step, upward trace signifies COP displacement to right. For non-paretic step, downward trace signifies COP displacement to left. Paretic step absolute displacement graphically 3x greater than non-paretic step.

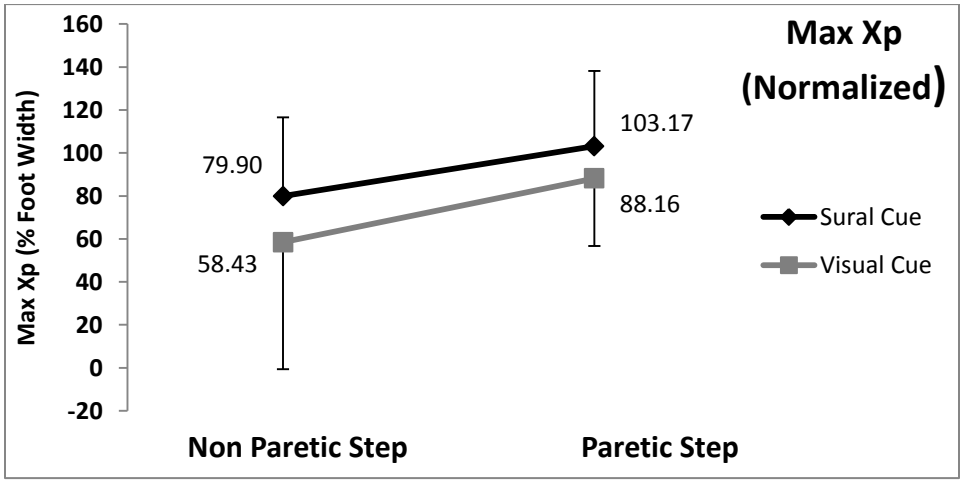


Figure 19: Pooled mean data for net Max Xp (medial-lateral displacement). Sural cue produced greater Xp displacements but was not statistically significant. Stepping with the paretic limb produced significantly greater Xp displacements; estimated 18% of average foot width greater Xp displacement with paretic step.

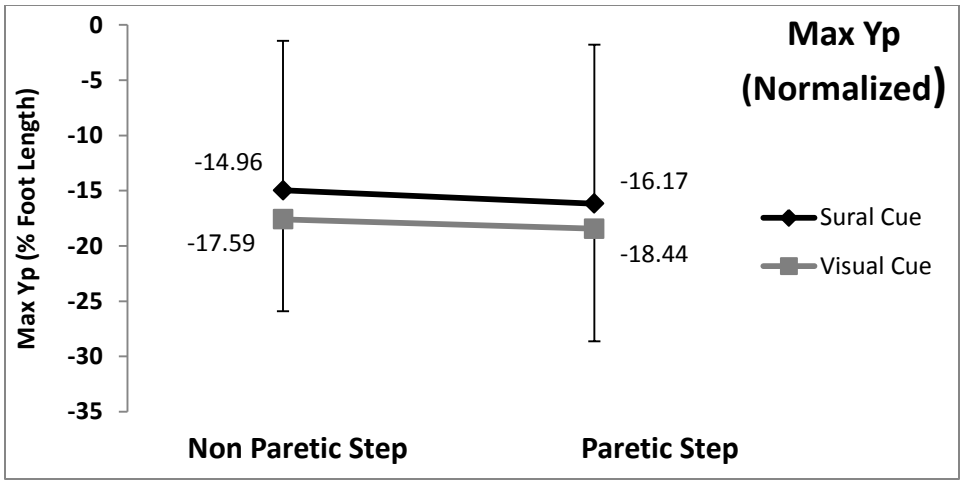


Figure 20: Pooled mean data for net Yp displacements. Sural produced slightly greater Yp displacements. No statistical differences between cue or stepping limb.

6.6 My and Mx Moments

The effects of cueing (sural or visual), stepping limb (paretic and non-paretic) and action (loading and unloading) on the change in Mx were analyzed with a three-way ANOVA model. The change in Mx was significantly (p =0.0018) greater in the non-paretic stepping limb compared to the paretic stepping limb. Figure 21 is a representative example of the differences in Mx on the paretic limb compared to the non-paretic limb. The estimated change in Mx was 1.5 %BW/m more with the non-paretic stepping limb than for the paretic stepping limb with a 95% CI (.55 % BW/m, 2.34 % BW/m). Pooled data shows the difference in Mx on the paretic limb compared to the non-paretic limb across subjects (Fig.22). There were no statistically significant differences in the change in Mx for the cue (p= 0.9564) or whether or not the subject was stepping with the paretic or non-paretic limb (p = 0.1028).

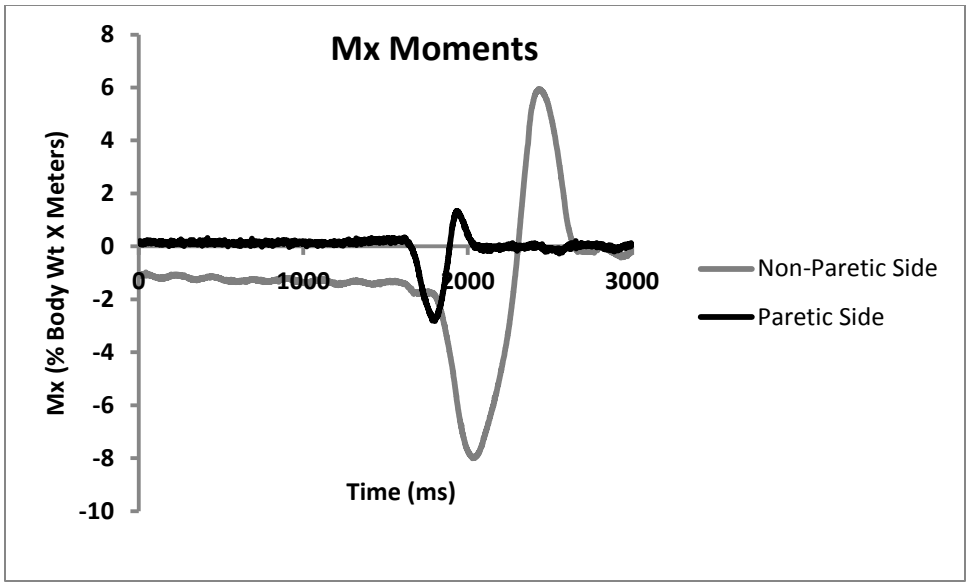


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Figure 21: Representative example of significantly larger Mx moments on non-paretic limb compared to paretic limb. Both moments are going in posterior direction (as expected) but with significantly greater contribution from the non-paretic limb.

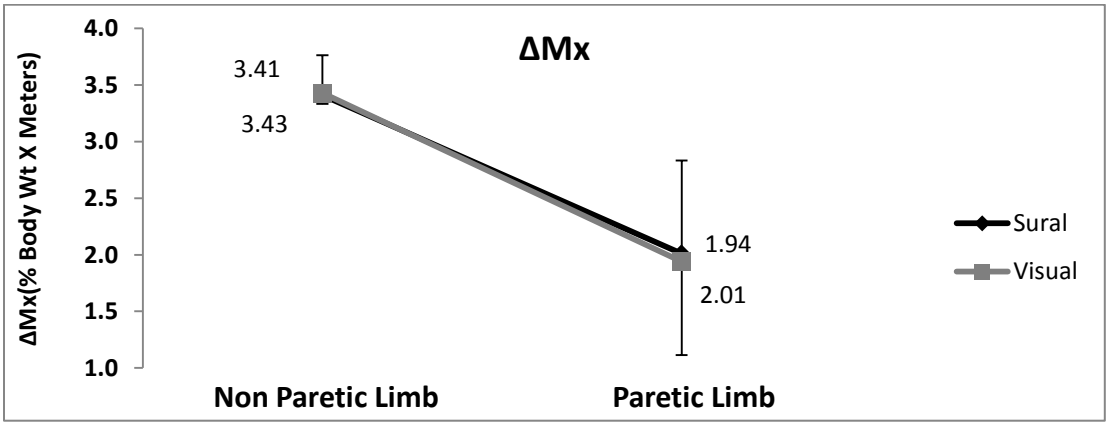


Figure 22: Pooled mean data of the change in Mx moment. Non-paretic limb had significantly greater Mx moments compared to paretic limb; estimated change 1.5 % BW/m greater on non-paretic limb compared to paretic limb. No significant differences in Mx moments for cueing

The effects of cueing (sural or visual), stepping limb (paretic and non-paretic) and action (loading and unloading) on the change in My were analyzed with a three-way ANOVA model. There was not a statistically significant difference in the change of My

with the sural or visual cue (p = 0.2716) or when the subject was stepping with the paretic or non-paretic limb (p = 0.3777). The change in My in the non-paretic limb was marginally significantly greater than the paretic limb (p = 0.0776). Figure 23 shows pooled data results for My moments.

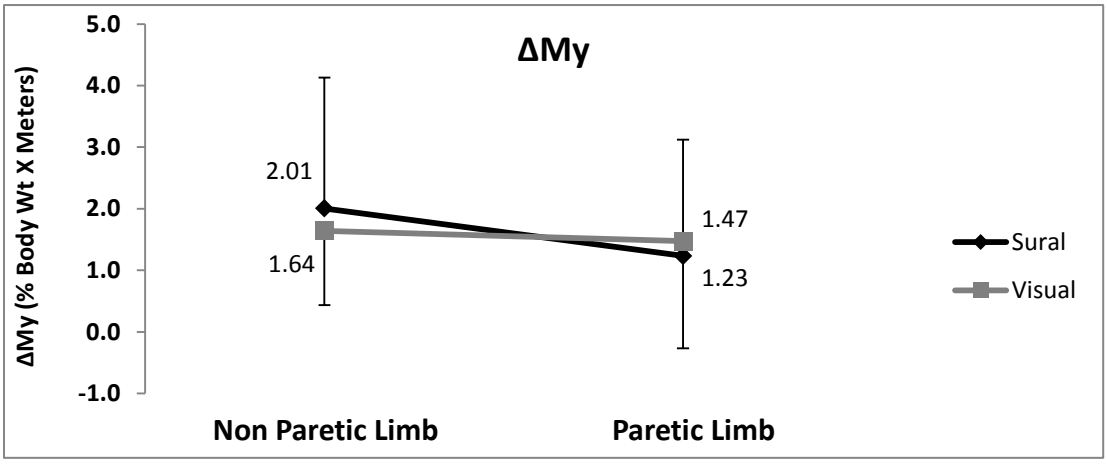


Figure 23: Pooled mean data for change in My moments. My changes showing greater change on non-paretic limb approaching statistical significance (p = 0.0776).

Electromyography (EMG)

6.7 EMG Reaction Times

The effects of cueing (sural or visual), stepping limb (paretic and non-paretic) and action (loading and unloading) on the TA reaction time of the subjects were analyzed with a three-way ANOVA model. The TA reaction time was statistically (p <0.0001) faster with the sural cue compared to the visual cue for both ipsilateral (Fig. 24 A) or contralateral (Fig.24 B) TA activity. The estimated TA reaction time was 189ms faster with the sural cue compared to the visual cue with a 95% CI (141ms, 237ms). Figure 25

(A & B) show pooled data for the TA reaction times. The difference in the TA reaction time was not statistically significant for the paretic and non-paretic muscle ($p = 0.5806$).

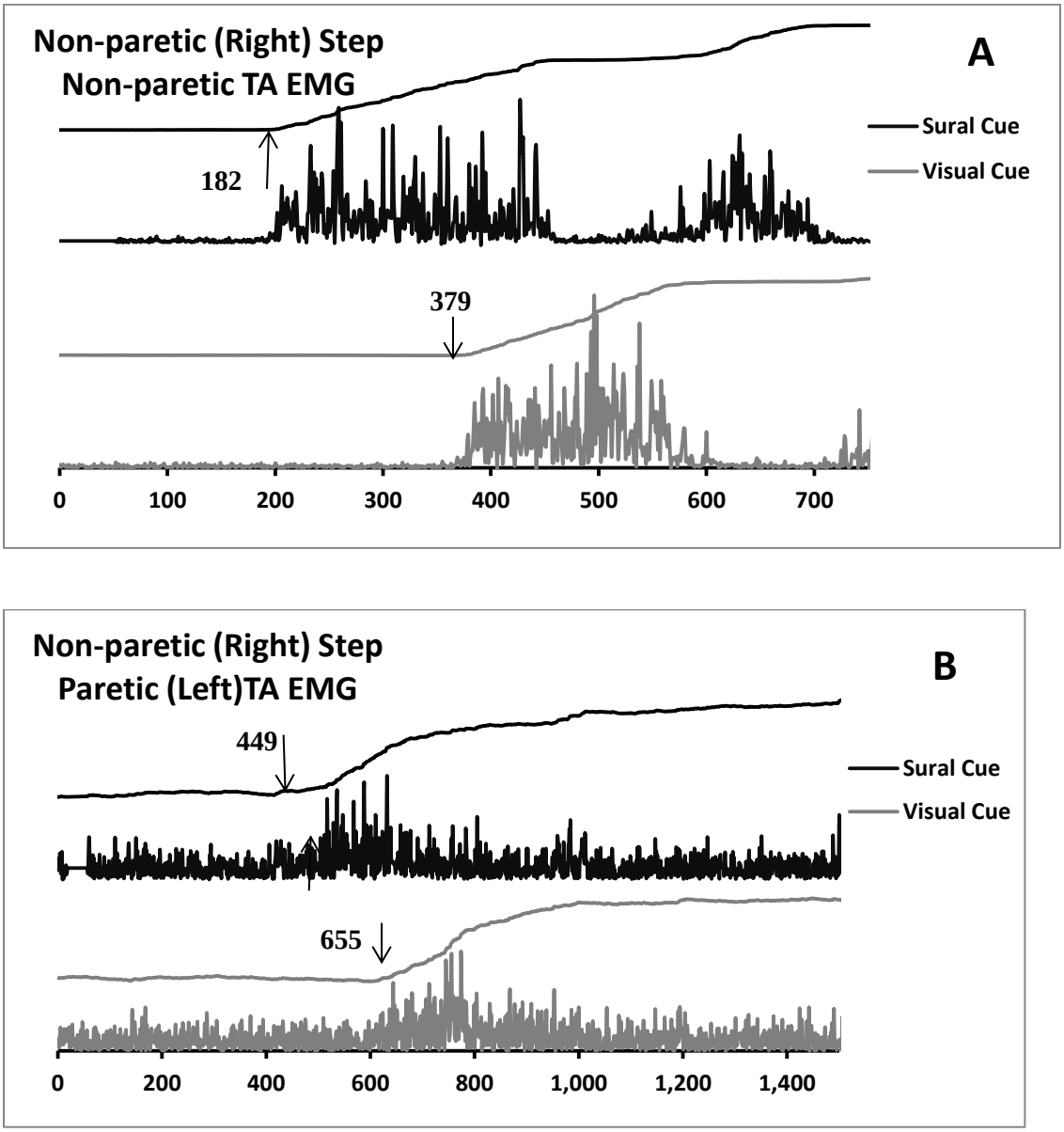
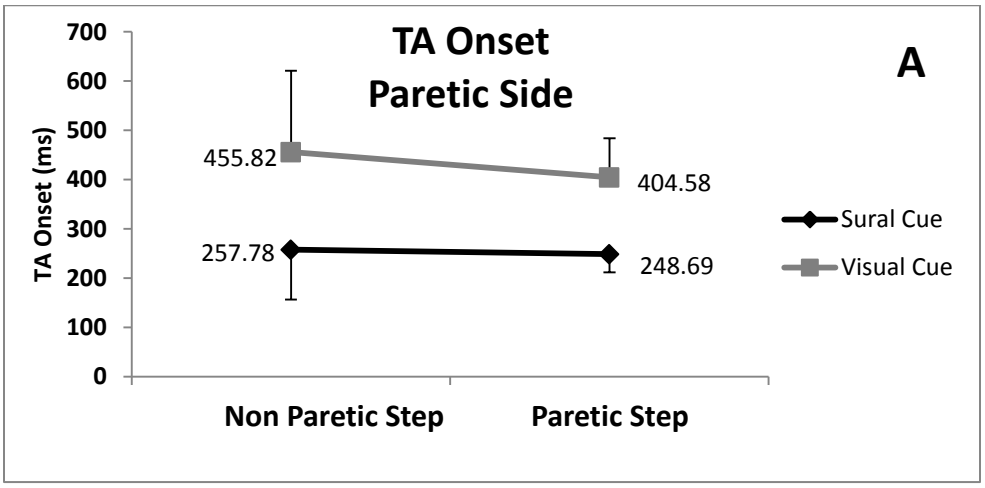


Figure 24: Representative example of TA reaction time significantly faster with sural cue compared to visual cue. Cue on at time = 0. (A) Non-paretic TA with non-paretic step. Sural reaction time = 182ms; visual reaction time = 379ms. (B) Paretic TA with non-paretic step. Sural reaction time = 449ms; visual reaction time = 655ms.



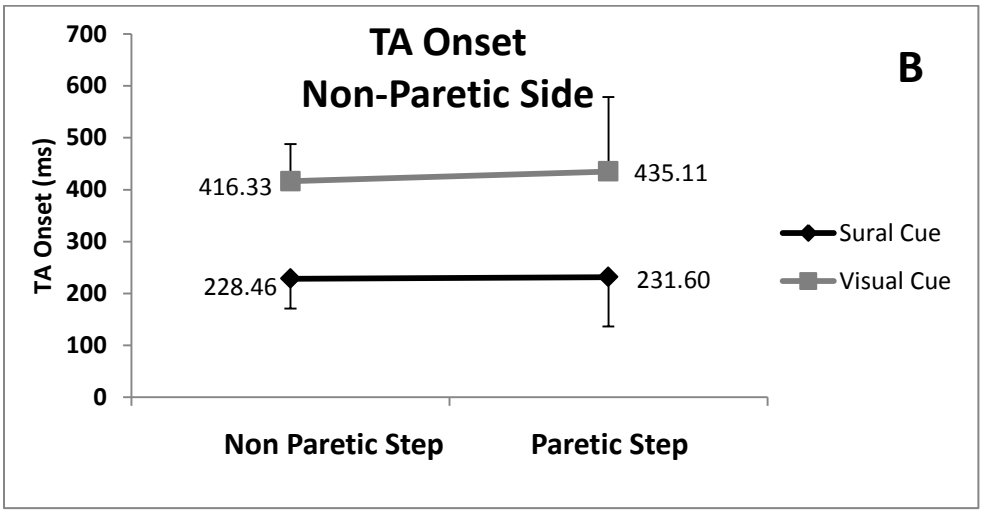


Figure 25: Pooled mean data for TA onset. The sural cueing produced faster TA onset on the paretic TA (A) and the non-paretic TA (B) regardless of stepping limb or side of measurement; estimated 189ms faster TA onset with sural compared to visual.

The effects of cueing and limb (paretic or non-paretic) on the GM reaction time RT when the subject was stepping were analyzed in a two-way ANOVA model. The GM RT was significantly (p <0.0001) faster with the sural cue compared to the visual cue. Figure 26 depicts a representative example of GM RT; sural cue produced faster GM

onsets compared to visual cue. The estimated GM RT was 206 ms faster with the sural cue than for the visual cue with a 95% CI (156ms, 257ms). Figure 27 is a summary of the pooled data for GM RT. There were no statistically significant differences in the GM RT when the subject was stepping with the paretic limb or stepping with the non-paretic limb ($p = 0.2698$).

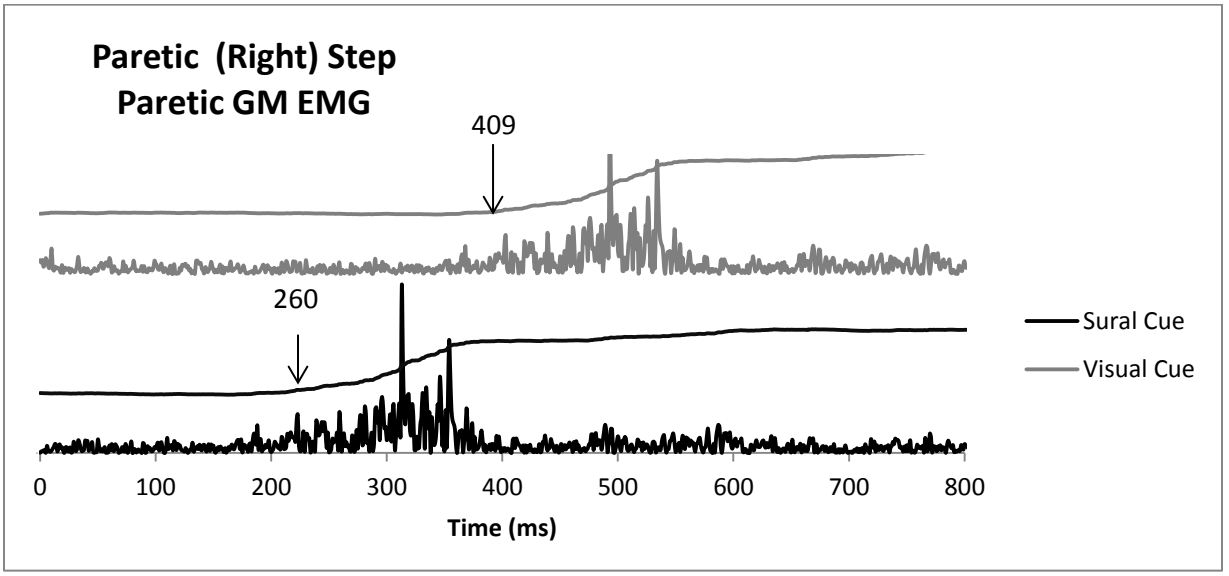


Figure 26: Representative example of GM reaction time significantly faster with sural. Figure shows paretic GM with paretic stepping. Sural reaction time = 260ms; visual reaction time = 409ms.

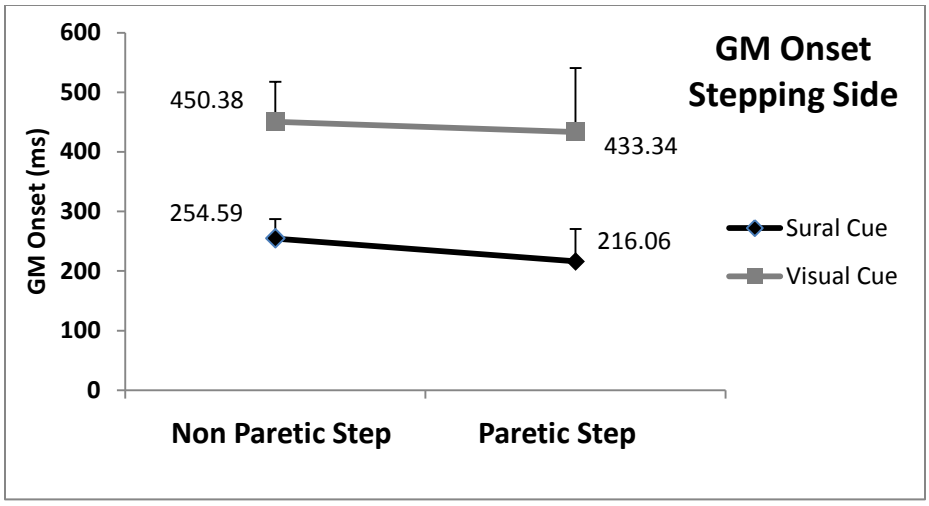


Figure 27: Pooled mean data shows sural cue produced faster GM RT; estimated 257ms faster onset with sural cue compare to visual cue. No statistical differences when stepping with paretic or non-paretic limb.

6.8 EMG Activity

The effects of cueing and limb (paretic or non-paretic) on the normalized paretic TA when the subject was stepping were analyzed with an ANOVA model. Paretic TA EMG activity was 124% ($p = 0.0014$) greater when stepping with the non-paretic limb compared to stepping with the paretic limb with 95% CI (54 %, 194 %)(Fig. 28). There was not a statistically significant difference in the paretic TA EMG activity when presented with the sural or visual cue ($p = 0.5942$).

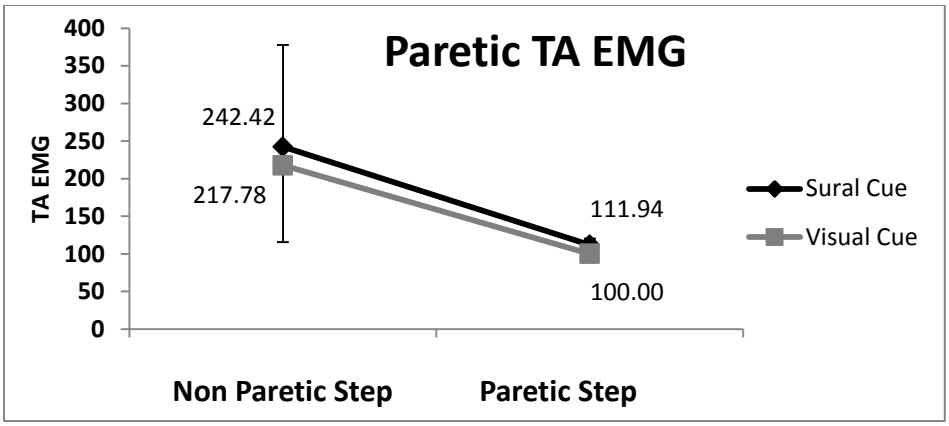


Figure 28: Pooled mean data for the paretic TA muscle. Significantly more paretic TA EMG with non-paretic step compared to paretic step; estimated 124% more paretic TA EMG with non-paretic step. Cueing had no significant effects on the paretic TA EMG.

Similarly, the effects of cueing and limb (paretic or non-paretic) on the normalized non-paretic TA when the subject was stepping were analyzed with an ANOVA model. The non-paretic TA EMG activity was 54% (p = 0.0009) greater when stepping with the paretic limb compared to stepping with the non-paretic limb with a 95% CI (24%, 86%)(Fig. 29). The difference in the non-paretic TA EMG activity when presented with the sural or visual cue was not statistically significant (p =0 .7840).

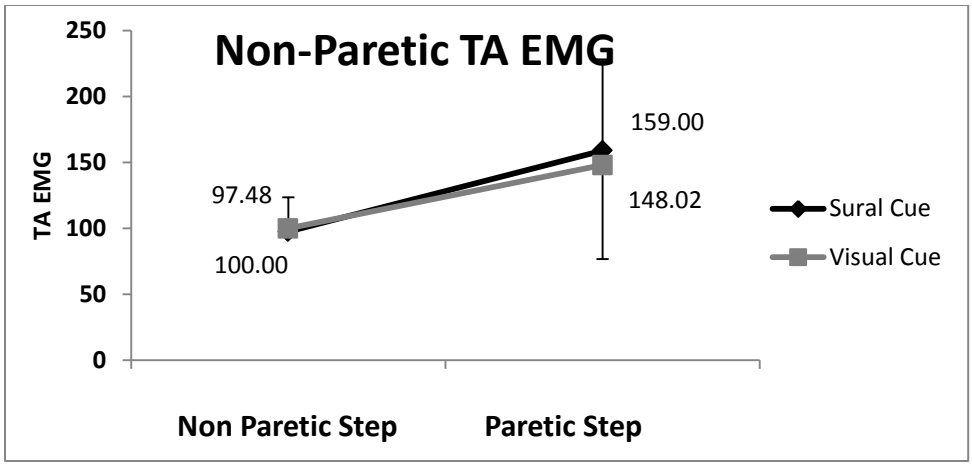


Figure 29: Pooled mean data for the non-paretic TA muscle. Significantly more non-paretic TA EMG with paretic step compared to non-paretic step; estimated 54% more non-paretic TA EMG with paretic step. Cueing had no significant effects on the non-paretic TA EMG.

The effects of cueing and limb (paretic or non-paretic) on the normalized GM EMG activity when the subject was stepping were analyzed with an ANOVA model. There was not a statistically significant difference in the GM EMG activity when presented with the sural or visual cue (p =0 .6747) or when the subject was stepping with their paretic or non-paretic limb (p = 0.9920). Figure 30 depicts summary data for GM EMG.

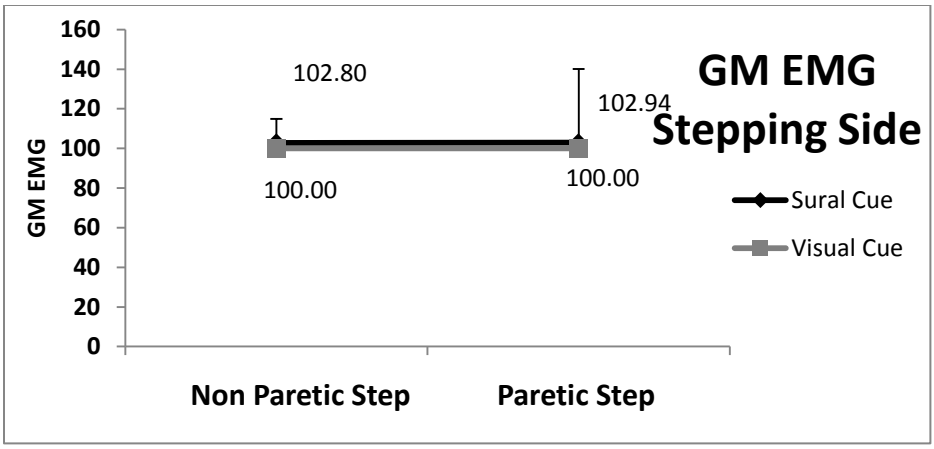


Figure 30: Pooled mean data for GM EMG. No significant differences between sural and visual cue and non-paretic or paretic stepping.

Baseline Loading – Standing Symmetry

The effects of the leg condition and the random subject effect on the loading difference at quiet stance were analyzed with a mixed ANOVA model. There was a significant loading difference at quiet stance between the paretic and non-paretic limb ($p = 0.0383$). The non-paretic limb was loaded an estimated 9% BW more than the paretic limb with (6.5% BW, 11.5% BW) 95% CI. The random subject effect was not statistically significant ($p > 0.99$). Figure 31 depicts the asymmetric loading towards the non-paretic side. This figure summarizes Fz loading data at quiet stance under both cueing (visual and sural) and stepping conditions (paretic or non-paretic). In all conditions the subjects on average demonstrated a significantly greater loading on their non-paretic compared to their paretic limb prior to receiving a ready or go cue.

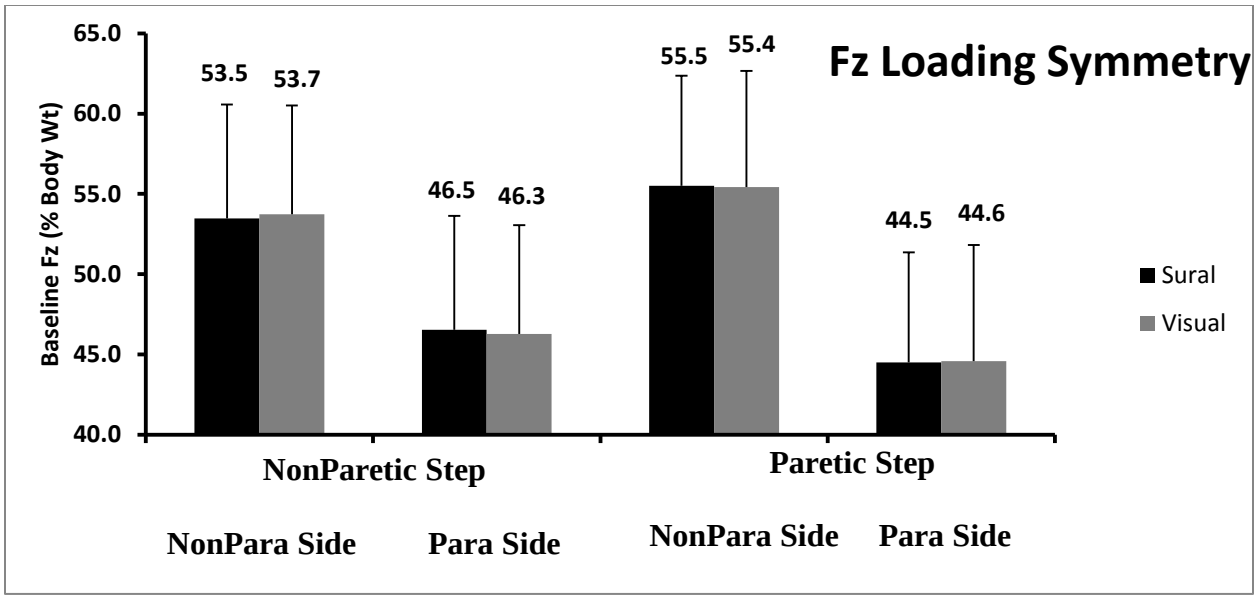


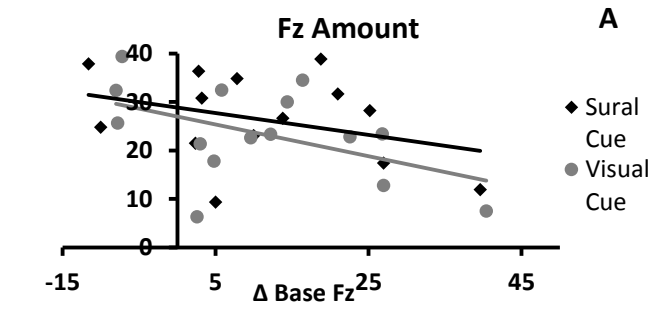
Figure 31: Fz loading symmetry at quiet stance prior to subject receiving a ready or go cue. Subjects loaded an average 9% BW more on the non-paretic limb compared to the paretic limb. This asymmetric loading stance was consistent with both cueing conditions and stepping limb conditions.

The parameter estimates of the model revealed that there were certain subjects with an estimated mean difference from the reference subject. That is, some subjects loading at quiet stance were statistically different compared to each other, but the overall subject effect was not statistically significant in the model. For example, the estimated difference between subject 4 and 15 was 15 % BW ($p < .001$). Further investigation of the model revealed that eight out of the fifteen subjects (8/15) had statistically significant differences in loading symmetry even though on average the subject effect was not statistically significant. This difference warranted further exploration including repeating some of the previous analysis with the difference in the quiet stance loading or symmetry of subject as an independent variable in some of the previous models.

The dependent variables were fit again with a multiple linear regression (MLR) model to analyze the independent loading symmetry in stance (the difference between

paretic and non-paretic Fz loading at quiet stance) variable in conjunction with the other covariates such as cue and stepping limb. Four dependent variables were significantly correlated to standing symmetry: 1) Net Yp excursion; 2) Yp onset; 3) Loading speed; 4) Loading amount.

The loading amount was significantly (p = 0.0135) 3.2 %BW more for every 10% percent increase in the amount the subject was loaded to their paretic limb versus their non-paretic limb (95% CI for the increase is 0.7 to 5.7 %BW) (Fig.32 A). The speed of loading was significantly (p = 0.0070) 36.4 % BW/s more for every 10% increase in the amount the subject was loaded to their paretic limb versus their non-paretic limb (95% CI for the increase is 10.8 to 62.0 % BW/s) (Fig.32 B). Net Yp was significantly (p = 0.0029) 4.2 % foot length less for every 10% increase in the amount the subject was loaded to their paretic limb versus their non-paretic limb (95% confidence interval for the decrease was 1.0 units to 6.9 % foot length) (Fig. 32C). Net Yp onset was significantly (p = 0.0396) 21.1 ms more for every 10% increase in the amount the subject was loaded to their paretic limb versus their non-paretic limb (95% confidence interval for the increase is 1.1 ms to 41.1 ms) (Fig. 32D). Three of the dependent variables were not significantly correlated to standing symmetry; net Xp excursion (p = 0.904) and reaction time (p = 0.0716) and Fz reaction time (p = 0.4531).


Fz Amount
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10
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-15
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25
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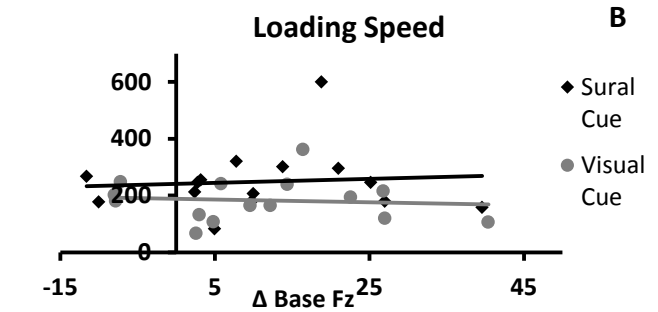
Δ Base Fz
Sural Cue
Visual Cue


Loading Speed
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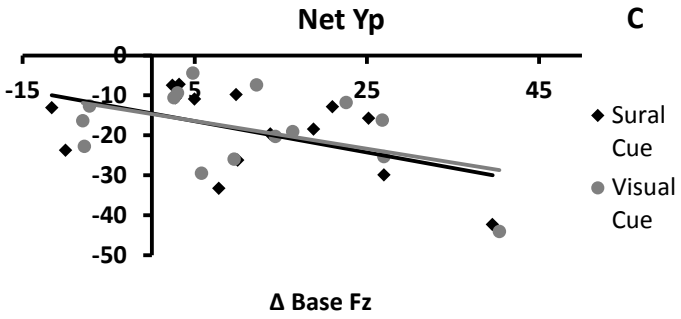
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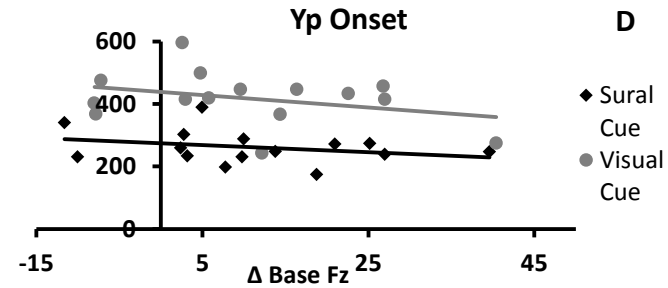
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Sural Cue
Visual Cue

Figure 32: Correlation plots for 4 dependent variables. Horizontal axis is difference in baseline loading where zero = no difference in limb loading; right of zero is > loading on non-paretic; left of zero is > loading on paretic. All data points are under condition of paretic limb stepping (loading). (A) Amount of Fz loading increases with greater paretic limb loading. (B) Loading speed increase with greater paretic limb loading. (C) Net Yp increase with greater non-paretic limb loading. (D) Yp onset slower with greater paretic limb loading. All results show trends of sural positively impacting the variable; only Yp onset had statistically significant difference with sural compared to visual.

Chapter 7: Discussion

This study investigated the effects of cueing on the step initiation APAs and reaction times in stroke survivors. The subjects were relatively highly functioning survivors, predominantly left hemiplegics with a wide range of ages and years since stroke. They were cognitively intact, had a range of motor impairments and had a high level of confidence in their balance abilities. These individuals would not be unlike individuals seeking rehabilitative services across the continuum of care.

7.1 Reaction Times

A robust and significant finding in this study was the influence of sural nerve cueing on reaction times. All five of the reaction time variables were significantly reduced with the sural cue: 1) Fz loading; 2) Net Xp; 3) Net Yp; 4) GM EMG; 5) TA EMG. The sural effect was significant regardless of limb (paretic or non-paretic) or action (stepping or standing). Vertical loading reaction times were statistically faster with the sural cueing regardless of limb (paretic or non-paretic) or action (stepping or standing), proving to be a powerful factor in the release of the APA. The sural cue also produced significantly faster net Xp and Yp reaction times regardless of limb or action.

Furthermore, both the TA and GM onsets were significantly faster with the sural cue. These data are consistent with results in a similar paradigm but with healthy young adults. [31,48]

A sural cue initiated vertical limb loading, lateral and posterior COP shifts and muscular activity within the APA faster, regardless of the limb or stepping situation. This result has important implications related to gait initiation and fall prevention because it has demonstrated a means by which reaction times in stroke survivors can be changed for the better. In that postural control is a complex interaction between an individual and their environment, the utility of improved reaction times is important. Two areas of function have the potential to be impacted by reduced reaction times: walking (gait initiation) and fall prevention (improved balance reactions).

A progressive neurologic disease with a classic symptom of gait difficulties is Parkinson's disease. Persons with Parkinson's disease have pervasive bradykinesia and profound gait initiation difficulty with disease progression. They have shown to have APAs with markedly reduced amounts of vertical loading and reduced COP excursions. [35,37,77] In these individuals, decreased reaction times may offer an easier release of a step to hasten gait initiation. If proven beneficial, one could imagine a portable sural stimulation device may offer ongoing relief from gait related motor blocks.

A second aspect of function deals with the recovery of balance upon perturbation. There is some conflicting evidence about the prevalence of an APA and the role that it plays in balance recovery, particularly within a compensatory stepping response paradigm. One study found APAs were consistently present but diminished with pre-

planned stepping responses [78] while others found APAs to exist in approximately 50% of the subjects under experimental balance perturbations. Admittedly, if APAs are not critical for successfully executing a compensatory step, the value in changing them may be limited. However, a different study found that the amplitude of the APA was significantly correlated to step latency, demonstrating that those subjects with "enhanced" APAs (larger Fz amplitudes) had a shorter latency of the stepping foot lifting off the ground. [79]

In either case, the possibility of improving the ability to more easily begin walking or prevent a possibly injurious fall is intriguing. Bearing in mind that stepping reaction times were found to be the most important predictor of falls, [14] the next important question becomes whether or not reaction times can be modified through training.

There is evidence that reaction times can be improved in both healthy young and older adults and in stroke survivors. For example, finger and wrist extension on the paretic upper extremity had significantly improved reaction times to an auditory signal after rehabilitative treatments [80,81]. In a step training paradigm study with healthy younger and older subjects, step initiation time for both groups was reduced with training. [82] A single case study on a 68 year-old stroke survivor reported a decrease in step reaction time after rapid step training. [83] Other investigators have demonstrated the ability to improve components of compensatory stepping under a variety of experimental situations in healthy and neurologically involved adults. [84,85]

Despite good evidence that stepping reaction times can be improved, there is no known literature exploring whether or not APA reaction times can be trained and if so, would the training impact one's ability to execute a step any faster or easier. This study confirmed that sural cueing had a positive impact on the reaction times associated with step initiation APAs in stroke survivors. A logical next step might be a study designed to train APA reaction times using a sural cue in a voluntary step paradigm with neurologically impaired adults. If results were favorable, further probing of the effects of APA reaction time training and its impact on compensatory stepping strategies would be interesting.

7.2 Speed of Loading

When the speed of loading (dFz/dt) was evaluated as it related to the action of the limb (loading or unloading), a pattern of dominance emerged on the non-paretic limb. The paretic limb loaded and unloaded an estimated 50% BW/s and 58% BW/s, respectively, faster than the non-paretic limb. The sural cue significantly increased the speed of loading by an estimated 44% BW/s faster. Although statistically non-significant ($p = 0.0804$), the sural had an estimated 40% BW/s increase in speed of unloading compared to the visual cue.

Although these results imply a dominant role for the paretic limb, it is unlikely that the faster loading and unloading on the paretic limb was due to superior performance of that limb. Two separate sets of data dealing with EMG activity and the moments contributing to the net COP refute the paretic limb's dominance in loading. Paretic limb EMG was at worst, absent and at best, inconsistent. The sporadic, often low level

activity indicated an overall reduced neuro-muscular engagement from the paretic limb in the execution of the APA. Moreover, the Mx moments showed a significantly greater contribution to the posterior net COP movement from the non-paretic limb compared to the paretic limb. Finally, Mx moments for the two limbs were often seen to be in opposition of one other with the paretic limb moment in the wrong direction (see section 7.4 below)

An alternative hypothesis explaining this result is that of non-paretic limb dominance. It may be that the increase in speed results from the non-paretic limb pushing towards the paretic limb (to load the paretic limb) or pulling away from the paretic limb (to unload the paretic limb) in order to generate the APA. Limb loading and lateral displacement of the COP is due to activation of the stepping limb glueteus medius and the impending stance limb adductor magnus. We monitored stepping limb gluteus medius and saw sporadic or poor activation of that muscle. We did not monitor the contralateral adductor but we would predict it to be overly active to generate the appropriate forces for initiating the step. Future experiments should directly address this issue.

7.3 Loading Amount

There was a statistically significant but modest increase in the amount of loading of the paretic limb (5% BW) compared to the non-paretic limb. The differences in cue were non-significant. This variable was analyzed only under the loading condition. Therefore, these subjects had greater vertical loads when they stepped with their paretic limb. Considering that statistically, these subjects were loaded an estimated 9% BW

more on the non-paretic limb at quiet stance, these results dispute previous data showing vertical loads increased proportionately with greater stepping limb loading at stance. [86] However, an important difference exists; Patchay's study used healthy, young adults standing asymmetrically. It may be that healthy adults may have more kinetic and kinematic options available to solve the problem of asymmetrical loading and are therefore able to select the most efficient solution to release the step. Stroke survivors may have limited options due to impairments related to cortical damage and therefore find a unique way to release a step.

7.4 Center of Pressure

The net COP displacement had less impressive changes than other dependent variables. The only variable showing significant change was that of net Xp displacement. On average, there was an 18% greater displacement in the medial-lateral direction when subjects were stepping with the paretic limb compared to the non-paretic limb. The net Yp displacement was not significantly impacted by the action of the limb (stepping or standing). Neither the net Xp nor the net Yp were significantly altered with the sural cue.

A possible explanation for the non-significant results in the Yp direction may be related to the inter-limb contributions to that movement. A closer look at the contributing moments (Mx and My) to the net COP highlighted some disproportionate inter-limb influences. The change in the non-paretic Mx was significantly greater after accounting for the stepping limb and the cue. In 7 of the 15 subjects the paretic Mx opposed the non-paretic Mx moment in 90-100% of the stepping trials. Fig. 33 illustrates a representative Mx tracing of one of the seven subjects with this pattern of movement. An

eighth subject had opposing Mx moments but only in a handful of trials. It is reasonable to deduce that if the limbs are opposing one another in an effort to move the COP posteriorly, the overall displacement (Yp) will be diminished. Figure 35 (C) depicts the net COP displacement for a subject taking a step with their right paretic limb. The posterior COP displacement is only about 1 cm and when the Mx moments were examined, they were found to display the dissociation shown in figure 33.

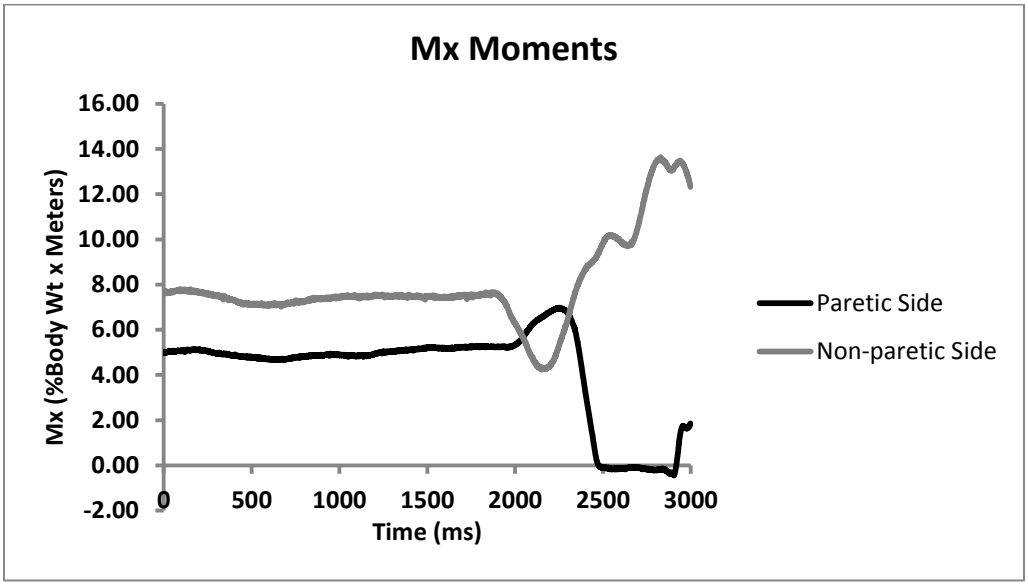


Figure 33: Representative example of opposing Mx moments for the paretic and non-paretic limb. Subject taking a right (paretic) step. The moment of the non-paretic limb shows typical (expected) deflection downward. The moment of the paretic limb shows an atypical deflection upward, opposing the non-paretic limb.

In contrast to the Mx moments, the My moments appeared far more organized in efforts to generate the medial-lateral COP movement of the APA. Although not statistically significant, the overall change on the non-paretic My was trending towards a

greater excursion than the paretic My. The limb action or cue had no significant impact on the My moments.

There are several possible explanations for this finding of consistently opposing Mx moments in nearly half of the subjects in this study. Pilot data on one healthy, older individual showed opposing Mx moments were consistently present as part of the APA. All other aspects of the APA were very typical. When net COP tracings from the pilot data were examined more closely on the APAs that had opposing moments, it appeared that the individual was rocking in an anterior-posterior direction during the APA. This rocking motion could explain the opposing Mx moments but have nothing to do with hemiparesis. Rather, it may simply be an adopted strategy through which the person releases a step.

Four of the seven subjects with opposing moments had minimal physical impairments (Fugl-Meyer $\geq$ 30/34). Despite what most would consider an excellent physical recovery from a stroke, there were lingering movement patterns that may have been acquired early on in recovery when neuro-motor control may have been severely compromised. Whether this rocking pattern that created the opposing Mx moments was a result of disorganized movement strategies from the motor control impairments, or a pre-existing strategy cannot be discerned from this study. If it was an acquired movement pattern, perhaps it is the result of limb dominance following the hemiplegia, learned non-use or learned inappropriate use of movement patterns in an attempt to recover walking abilities following recovery from the stroke.

The appearance of these opposing moments in both a healthy individual and stroke survivors highlights the gaps in knowledge related to step initiation. It's plausible that with the opposing moments reducing the net Yp displacement, the overall APA (and therefore step) of an individual who has a rocking pattern is less efficient at propelling the COM towards the impending stance limb in order to initiate a step.

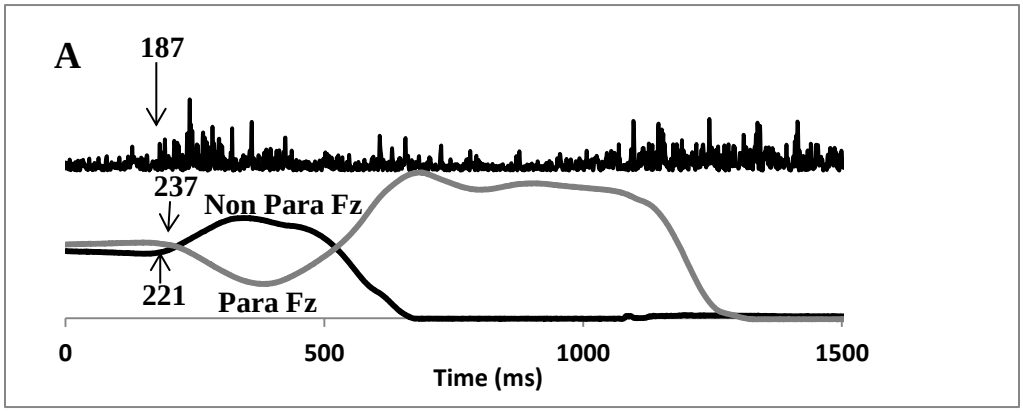
7.5 EMG Activity

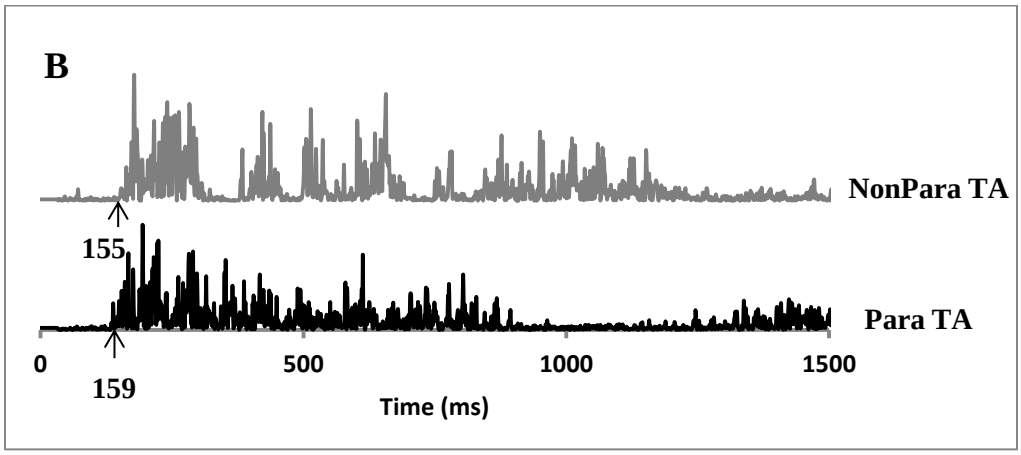
Onsets notwithstanding, none of the EMG dependent variables were significantly impacted by the sural cue. Furthermore, GM EMG activity was not impacted by whether or not it was the paretic or non-paretic limb stepping. However, the action of the limb did appear to influence the TA EMG activity. The paretic TA had over 100% more EMG activity on average when the subjects were stepping with the non-paretic limb. This is a dramatic increase in muscle activation and may prove to be a very powerful paradigm within which therapist can train patients. This increased paretic TA EMG activity when stepping with the non-paretic limb was also found in a more recent study of stroke survivors and gait initiation. [87] In contrast, the non-paretic TA had significantly more activity when the subjects were stepping with the paretic limb. Both of these results suggest that during the APA, the impending stance limb has enhanced TA activity. That finding has two important clinical implications. First, if the goal is to achieve more normalized EMG activity on the paretic limb, the intervention may be most effective to emphasize stepping with the non-paretic limb within the context of a rehabilitative session. This opposes what is often seen clinically; that is, stroke survivors have a preference for initiating gait with their paretic limb. This phenomenon is likely due to apprehension about loading the paretic limb. Second, initiating gait with the non-paretic

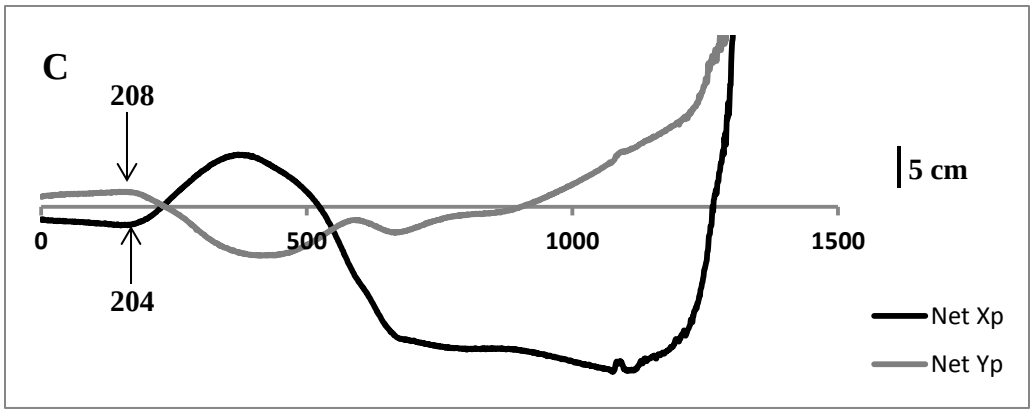
limb, thereby increasing overall paretic limb TA, might result in more effective posterior displacement of the net COP. [20] By doing so, the COM would be more effectively propelled towards the paretic limb and the release of the step more forthcoming.

The interpretation of these EMG results warrants some caution. The EMG data from the paretic limb was at times sporadic, low level, and inconsistent. Despite confirmation of proper electrode placement with concentric muscle contractions, it appears as though the muscles may have behaved very differently within the functional context of step initiation. Nevertheless despite very erratic, low level, often ill-timed muscle activity, the subjects in this study were able to generate a step including APA loading forces not unlike those found in healthy adults. Figures 34 and 35 illustrate two examples of the EMG and mechanical responses during step initiation. The first example (Fig. 34) shows a subject with a relatively typical-looking step initiation APA. The subject was high functioning with only minimal motor impairment (Fugl-Myer LE score was 32/34). The loading force (Fz) in this subject occurred 237 ms after the go cue (Fig. 34A) and was preceded by activation of the ipsilateral gluteus GM, a muscle believed to be a major contributor to vertical loading. Bilateral activation of TA (Fig. 34 B) preceded onset of the posterior displacement of the COP (Fig. 34C) by about 50 ms. The entire trajectory of COP displacement (Fig. 34D) was fairly typical with an initial posterior and lateral COP displacement followed by a projection anterior and over to the impending stance limb. The second example (Fig.35) highlights the discontinuity between the EMG and mechanical events of the APA that was often observed. This subject had more severe motor impairments (Fugl-Myer LE score was 20/34). This subject shows an Fz onset of the loading limb at 460 ms after the go cue with ***no***

activation of the ipsilateral GM. TA muscles, believed to be responsible for posterior COP displacement, occured substantially later (Fig. 35B) than onset of the posterior COP displacement (Yp) at 415 ms (Fig. 35C). Despite the impaired EMG pattern, the net COP displacement (Fig. 35D) was fairly typical.







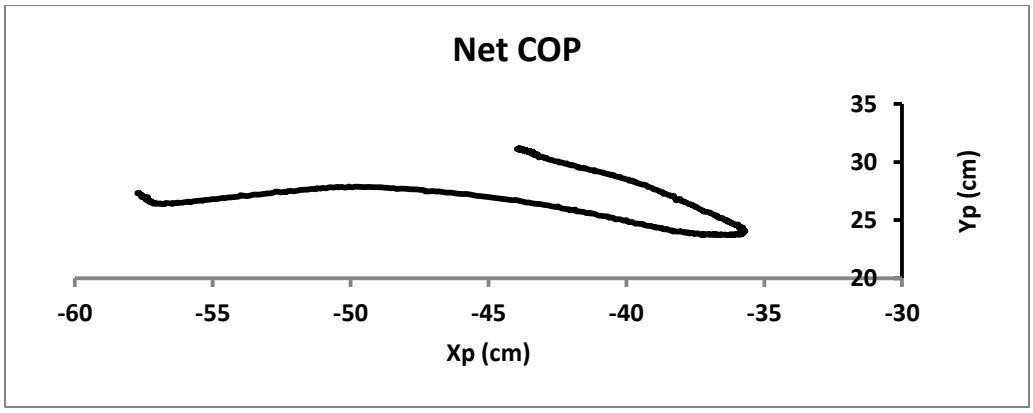
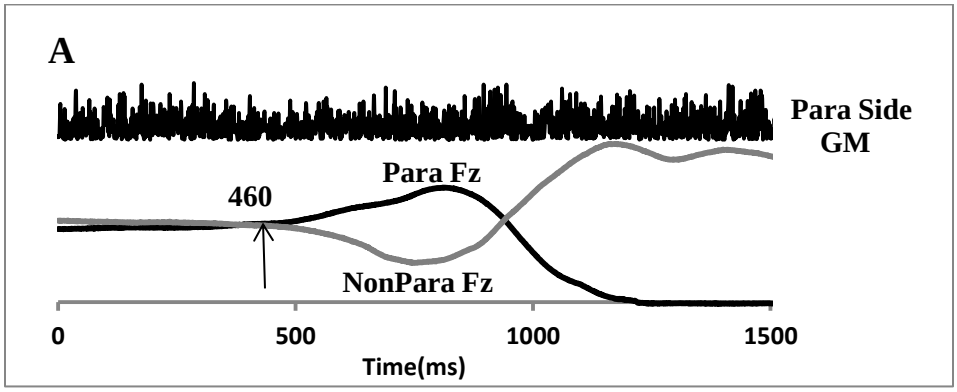
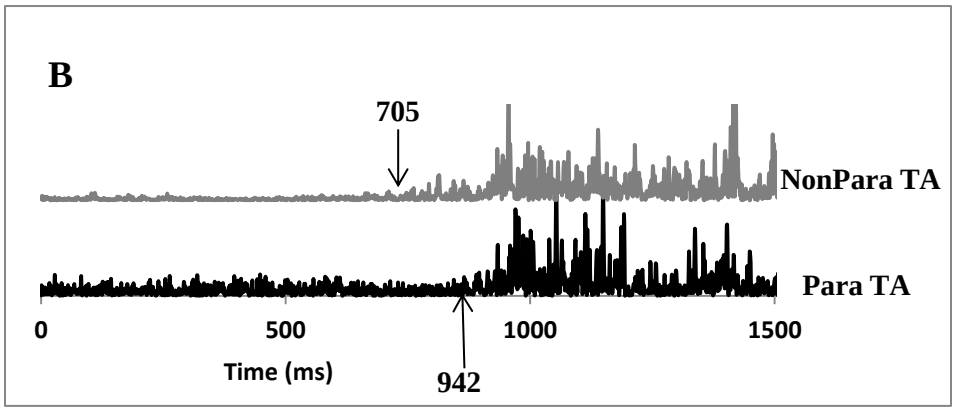


Figure 34: Typical APA production; subject with few motor impairments taking a step with their non-paretic right limb. Number with arrow refer to onset times following go cue at time = 0.(A) Stepping GM onset just prior to loading onsets. (B and C) Bilateral TA EMG onset precedes posterior COP displacement. (D) Net COP tracing shows typical lateral and posterior shift towards impending stepping limb followed by reversal back to impending stance limb.





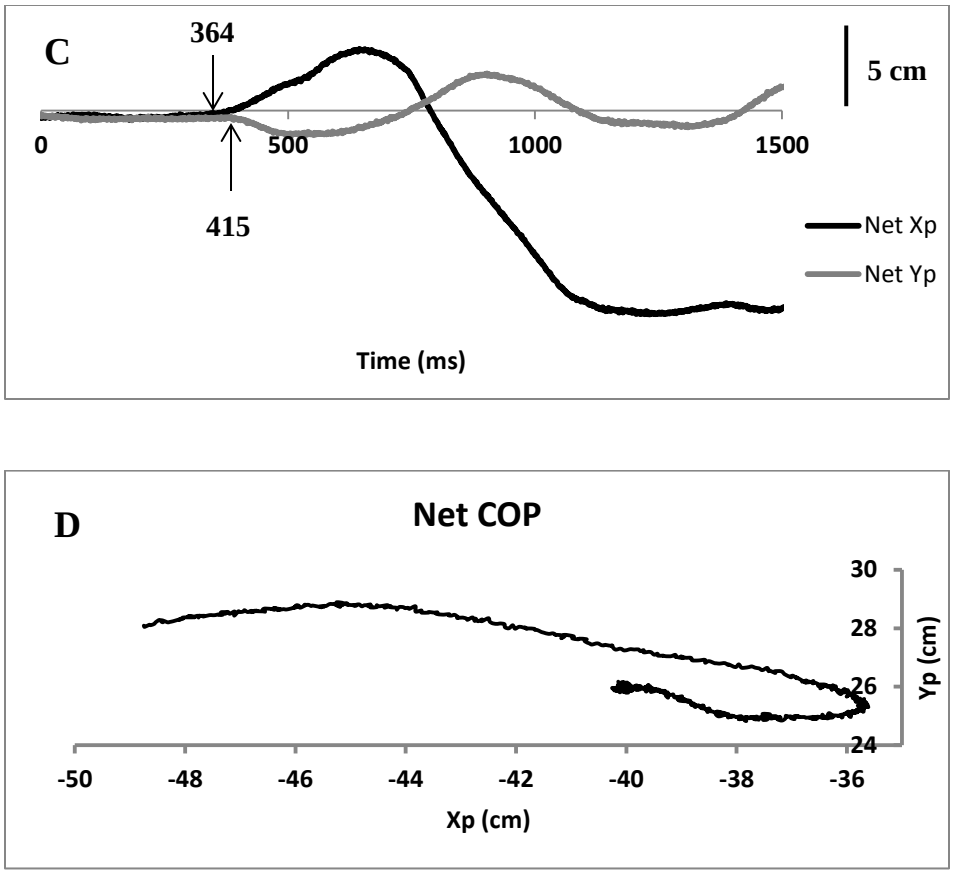


Figure 35: Atypical APA production; subject with greater motor impairments taking a step with their paretic right limb. (A) Stepping GM EMG shows no activity despite appropriate loading patterns. (B and C) Bilateral TA onset > 400ms after COP displacement onsets. (D) Net COP tracing shows typical lateral shift towards impending stepping limb, minimal posterior shift.

The disconnection between the neuromuscular and mechanical events of these APAs is an interesting finding and one that could query the assumptions underlying the current working definition of gait initiation APAs. It is highly likely that other movements influenced the APA and were not evaluated in this experimental set-up. For instance, a motion capture system would detect trunk or upper extremity movements that could influence the APA in an effort to compensate for muscular inabilities of the lower

limb. This was the case in one study investigating gait initiation in elderly with unilateral vestibular loss. [39,88] These authors observed arm movements in nearly all of the subjects who demonstrated appropriate posterior COP shifts with nearly absent TA activity during the APA.

These results indicate that subjects with hemiplegia due to stroke are able to generate appropriate loading forces and COP displacements without using muscles typically considered responsible for providing these mechanical events. Further research is needed to unravel how these subjects are generating the appropriate mechanical events associated with postural responses.

7.6 Standing Symmetry

Stroke survivors with hemiplegia are known to stand asymmetrically. [89-91] There is evidence that this asymmetry influences step initiation APAs. [40,46] In this study, there was a significant difference in limb loading with the non-paretic limb loading an average of 9% BW more than the paretic limb. Furthermore, eight out of the fifteen subjects had statistically significant differences in loading symmetry. Four dependent variables were significantly correlated to standing asymmetry (net Yp, Yp onset, Fz loading amount and speed). However, no interactions were found between these variables.

These results may offer some explanation for non-significant findings on certain dependent variables. For example, net Yp was found to have no significant differences when either the paretic or non-paretic limb was stepping or whether the subject was presented with a sural or visual cue. This correlation result suggests baseline loading may have influenced Yp displacement enough to reduce the effects of the sural cue.

This correlation data does not offer definitive answers regarding the impact of standing asymmetry or cue on step initiation APAs in stroke survivors. Only a subset of subjects had significant difference in loading asymmetries. Therefore the power of the analysis is compromised with such little data. Furthermore, this variable was only analyzed under paretic limb stepping. Further analysis under a variety of conditions, with greater subject numbers may offer more insight about the effects of asymmetry. Regardless, loading asymmetry warrants closer attention in future investigations on step initiation in stroke survivors.

7.7 Summary of Aims and Hypotheses Outcome

Aim 1: To compare and describe APAs associated with step initiation of individuals with hemiparesis due to stroke for two different go cues (visual and sural stimulation)

Hypothesis 1: Reaction times for vertical ground reaction force, medial-lateral and anterior-posterior center of pressure (COP) and tibialis anterior (TA) and gluteus medius (GM) onsets will not be shorter with sural stimulation go cue as compared to a visual go cue.

Outcome: Hypothesis 1 was rejected. Reaction times for vertical loading forces, both Xp and Yp COP onsets and EMG onsets were statistically faster with the sural compared to the visual cue regardless of limb action (stepping or standing) or location of measurement (paretic or non-paretic).

Hypothesis 2: The vertical ground reaction force, speed of force onset, medial-lateral and anterior- posterior COP, and TA /GM EMG of the stepping limb will not be enhanced with sural stimulation go cue as compared to a visual go cue.

Outcome: Hypothesis 2 was partially rejected. The loading speed and medial-lateral COP displacement were enhanced when presented with the sural cue compared to the visual. The sural cue had no statistically significant influence on the peak loading amount, posterior COP displacement or EMG.

Aim 2: To compare step initiation APAs of individuals with hemiparesis due to stroke when stepping to visual or sural go cue when stepping with the paretic vs. non-paretic leg.

Hypothesis 3: When stepping with either the paretic or non-paretic leg, there will be no difference in paretic or non-paretic leg contributions to COP excursions.

Outcome: Hypothesis 3 was partially rejected. The non-paretic limb had statistically significantly greater Mx contributions to the posterior COP displacement compared to the paretic limb. The Mx contributions to the medial-lateral COP displacement were trending towards a greater contribution from the non-paretic but did not meet statistical significance.

Hypothesis 4: When stepping with either the paretic or non-paretic leg, there will be no difference in paretic or non-paretic leg EMG contribution to the APA.

Outcome: Hypothesis four was partially rejected. The non-paretic TA EMG activity was significantly greater when stepping with the paretic limb. There were no differences in the GM EMG activity.

Aim 3: To describe the relationship, through linear regression, between the degree of asymmetrical standing to the influence of sural stimulation on reaction times and APA generation.

Hypothesis 5: The amount of standing asymmetry will not influence the shortening of reaction times produced by sural stimulation cuing.

Outcome: Hypothesis 5 partially rejected. Net Yp reaction was the only (reaction time) variable correlated to the sural cue. The Yp reaction time was not influenced by standing asymmetry.

Hypothesis 6: As the amount of standing asymmetry increases, the influence of sural stimulation on loading force, speed of force onset, COP excursions and EMG will be unchanged.

Outcome: Hypothesis 6 was accepted. None of the loading force or COP variables were significantly correlated to the sural cue.

7.8 Study Limitations and Future Research

This study was not designed to probe the central nervous system such that the mechanism through which the sural stimulation was impacting performance might be understood. Future investigations could explore cutaneous reflex pathways in stroke survivors similar to what has been done previously in our lab (for doctoral thesis) on healthy young adults. [48] Hajela hypothesized that the primary effects due to the cutaneous sural stimulus were mediated through cortical pathways. In view of Hajela's hypothesis the results of this current study are particularly intriguing considering the effects of the sural nerve input persisted despite cortical damage.

Subjects in this study had (primarily) cortical injuries. Including subjects with a wider range of cortical injuries may also help understand where or how the sural stimulation is impacting movement. Moreover, a broader inclusion criteria better reflects the variability of individuals seeking rehabilitation across the continuum of care.

An important aspect of necessary future research that emerged from this study was the need for ongoing investigation in to how stroke survivors initiate a first step. Although there are many articles addressing pieces and parts of that question, much about how this population figures out how to initiate a step is unknown. This is particularly evident as it relates to the movement of the net COP and the contributing moments from each limb as well as the disconnectedness of the EMG activity with the loading and COP patterns. Comprehensive studies using two force plates, motion analysis, and EMG that includes soleus and trunk musculature could help develop a body of knowledge describing the APA in stroke survivors.

Highly detailed, single subject studies may be one approach to elucidating some of the subtleties within the APA production in stroke survivors. Investigating APA production under different stepping paradigms (reaction time, self-initiated, perturbation) may provide understanding in to the contextual use of APAs. Studies aimed at reporting patterns, trends and relationships of step initiation strategies among stroke survivors will be invaluable for a greater understanding of experimental manipulation and eventually, clinical interventions for improving functional mobility in this population.

7.10 Conclusions

Stroke is the leading cause of long-term disability throughout the world. [92] The United States alone will spend over 65 billion dollars a year on stroke related care, including rehabilitation services. [93] Nearly two-thirds of individuals immediately post-stroke are unable to walk or require some kind of physical assistance, while a third of individuals at 3 months post-stroke continue to need assistance or are non-ambulatory. [94] Stroke survivors are also at a much higher risk to fall. [7,10,94] Consequently, a large portion of time spent in rehabilitation will be aimed at balance recovery and walking ability. Furthermore, reduced ambulatory status has been associated with decreased overall fitness level, cardiovascular health, reduced bone mineral density and increased fatigue. [95-99]

It has been shown that APA characteristics in stroke survivors are different than those of non-neurologically involved individuals. Some of those differences include reduced net COP displacements, slower loading reaction times, smaller loading forces, disrupted temporal patterns and EMG activations. [26,27,30] With these preparatory phases impaired, the ability to release a step may be severely impacted thereby influencing gait initiation and balance recovery after stroke.

This study was novel in its breadth and depth of investigating APAs in stroke survivors, and has revealed several important findings. The most pervasive effect of the sural cue was seen with significantly faster reaction times. This finding transcended all of the dependent variables; vertical loading, net COP movement and EMG activation. Not only were all of these variables favorably impacted, but the faster reaction times

occurred regardless of action (stepping or standing) or limb (paretic or non-paretic). As discussed previously, this widely impactful intervention (stimulus) could have important clinical application.

This study was designed to develop a greater understanding of the kinetics and kinematics of APAs and the influence of cueing on step initiation in stroke survivors in a long term effort to develop rehabilitative interventions aimed at rapid gait and balance recovery. Ultimately, the goal of rehabilitation is to maximize function, safety and quality of life following a stroke. A better understanding of how stroke survivors initiate gait is necessary to developing best practice strategies to reach these goals.

Bibliography

1. CDC - older adult falls - falls in nursing homes - home and recreational safety - injury center. http://www.cdc.gov/HomeandRecreationalSafety/Falls/nursing.html. Accessed 8/2/2013, 2013.

2. Fuller GF. Falls in the elderly. *Am Fam Physician*. 2000;61(7):2159-68, 2173.

3. Tinetti, M E Williams,C S. Falls, injuries due to falls, and the risk of admission to a nursing home. *N Engl J Med*. 1997;337(18):1279-1284.

4. Www.aoa.gov. http://www.aoa.gov/Aging_Statistics/future_growth/future_growth.aspx. Updated 2010. Accessed June 4, 2013.

5. Teasell R, McRae M, Foley N, Bhardwaj A. The incidence and consequences of falls in stroke patients during inpatient rehabilitation: Factors associated with high risk. *Arch Phys Med Rehabil*. 2002;83(3):329-333.

6. Nyberg LG, Y. Patient falls in stroke rehabilitation. A challenge to rehabilitation strategies. *Stroke*. 1995;26(5):838-842.

7. Davenport, R J Dennis, M S Wellwood, I Warlow,C P. Complications after acute stroke. *Stroke*. 1996;27(3):415-420.

8. Mackintosh, Shylie F H Goldie,Patricia Hill, Keith. Falls incidence and factors associated with falling in older, community-dwelling, chronic stroke survivors (> 1 year

after stroke) and matched controls. *Aging Clinical and Experimental Research*. 2005;17(2):74-81.

9. Mackintosh, Shylie Hill, Keith Dodd, Karen Goldie,Patricia Culham, Elsie. Balance score and a history of falls in hospital predict recurrent falls in the 6 months following stroke rehabilitation. *Arch Phys Med Rehabil*. 2006;87(12):1583-1589.

10. Forster AY, J. Incidence and consequences of falls due to stroke: A systematic inquiry. *BMJ.British medical journal*. 1995;311(6997):83-86.

11. Jørgensen, Lone Engstad,Torgeir Jacobsen, Bjarne. Higher incidence of falls in long-term stroke survivors than in population controls: Depressive symptoms predict falls after stroke. *Stroke*. 2002;33(2):542-547.

12. Rogers MW, Kukulka CG, Brunt D, Cain TD, Hanke TA. The influence of stimulus cue on the initiation of stepping in young and older adults. *Archives of Physical Medicine & Rehabilitation*. 2001;82(5):619-624.

13. Polcyn AF, Lipsitz LA, Kerrigan DC, Collins JJ. Age-related changes in the initiation of gait: Degradation of central mechanisms for momentum generation, , *Arch Phys Med Rehabil*. 1998;79(12):1582-1589.

14. Lord SR, Fitzpatrick RC. Choice stepping reaction time. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*. 2001;56(10):M627-M632.

15. Breniere Y, Do MC. When and how does steady state gait movement induced from upright posture begin? *J Biomech*. 1986;19(12):1035-40.

16. Brunt D, Lafferty MJ, Mckeon A, Goode B, Mulhausen C, Polk P. Invariant characteristics of gait initiation. *American Journal of Physical Medicine & Rehabilitation*. 1991;70(4):206-212.

17. Mann RA, Hagy JL, White V, Liddell D. The initiation of gait. *Journal of Bone & Joint Surgery - American Volume*. 1979;61(2):232-239.

18. Rogers MW, Pai YC. Organization of preparatory postural responses for the initiation of lateral body motion during goal directed leg movements. *Neurosci Lett*. 1995;187(2):99-102.

19. Brunt D, Liu SM, Trimble M, Bauer J, Short M. Principles underlying the organization of movement initiation from quiet stance. *Gait Posture*. 1999;10(2):121-8.

20. Crenna P, Frigo C. A motor programme for the initiation of forward-oriented movements in humans. *J Physiol (Lond)*. 1991;437:635-653.

21. Elble RJ, Moody C, Leffler K, Sinha R. The initiation of normal walking. *Movement disorders*. 1994;9(2):139-46.

22. Lepers R, Breniere Y. The role of anticipatory postural adjustments and gravity in gait initiation. *Experimental Brain Research*. 1995;107(1):118-124.

23. Carlsoo S. The initiation of walking. *Acta Anat*. 1966;65(1):1-9.

24. Winter DA, Patla AE, Rietdyk S, Ishac MG. Ankle muscle stiffness in the control of balance during quiet standing. *Journal of Neurophysiology*. 2001;85(6):2630-2633.

25. Pai YC, Rogers MW, Hedman LD, Hanke TA. Alterations in weight-transfer capabilities in adults with hemiparesis. *Phys Ther*. 1994;74(7):647-57; discussion 657-9.

26. Hesse S, Reiter F, Jahnke M, Dawson M, Sarkodie-Gyan T, Mauritz KH. Asymmetry of gait initiation in hemiparetic stroke subjects. *Archives of Physical Medicine & Rehabilitation*. 1997;78(7):719-724.

27. Bensoussan L, Mesure S, Viton JM, Delarque A. Kinematic and kinetic asymmetries in hemiplegic patients' gait initiation patterns. *J Rehabil Med*. 2006;38(5):287-294.

28. Brunt D, Vander Linden DW, Behrman AL. The relation between limb loading and control parameters of gait initiation in persons with stroke. *Arch Phys Med Rehabil*. 1995;76(7):627-634. doi: DOI: 10.1016/S0003-9993(95)80631-8.

29. Rogers M, Hedman LD, Pai Y. Kinetic analysis of dynamic transitions in stance support accompanying voluntary leg flexion movements in hemiparetic adults. *Arch.Phys.Med.Rehabil.* 1993;74:19-25.

30. Tokuno CD, Eng JJ. Gait initiation is dependent on the function of the paretic trailing limb in individuals with stroke. *Gait Posture*. 2006;24(4):424-428.

31. Kukulka CG, Hajela N, Olson E, Peters A, Podratz K, Quade C. Visual and cutaneous triggering of rapid step initiation. *Experimental brain research*. 2009;192(2):167-73.

32. Queralt A, Valls-Sole J, Castellote JM. Speeding up gait initiation and gait-pattern with a startling stimulus. *Gait Posture*. 2010;31(2):185-190.

33. Winter DA, Patla AE, Prince F, Ishac M, Gielo-Perczak K. Stiffness control of balance in quiet standing. *Journal of Neurophysiology*. 1998;80(3):1211-1221.

34. Rogers MW, Pai Y. Dynamic transitions in stance support accompanying leg flexion movements in man. *Experimental Brain Research*. 1990;81(2).

35. Hass CJ, Waddell DE, Fleming RP, Juncos JL, Gregor RJ. Gait initiation and dynamic balance control in parkinson's disease. *Arch Phys Med Rehabil*. 2005;86(11):2172-2176.

36. Hass CJ, Waddell DE, Wolf SL, Juncos JL, Gregor RJ. Gait initiation in older adults with postural instability. *Clin Biomech*. 2008;23(6):743-753.

37. Martin M, Shinberg M, Kuchibhatla M, Ray L, Carollo J, Schenkman M. Gait initiation in community-dwelling adults with parkinson disease: Comparison with older and younger adults without the disease. *Phys Ther*. 2002;82(6):566-577.

38. Stackhouse C, Shewokis P, Pierce S, Smith B, McCarthy J, Tucker C. Gait initiation in children with cerebral palsy. *Gait Posture*. 2007;26(2):301-308.

39. Henriksson M, Henriksson J, Bergenius J. Gait initiation characteristics in elderly patients with unilateral vestibular impairment. *Gait Posture*. 2011;33(4):661-667.

40. Patchay S, Gahery Y. Effect of asymmetrical limb loading on early postural adjustments associated with gait initiation in young healthy adults. *Gait Posture*. 2003;18(1):85-94.

41. Beaman CB, Peterson CL, Neptune RR, Kautz SA. Differences in self-selected and fastest-comfortable walking in post-stroke hemiparetic persons. *Gait Posture*. 2010;31(3):311-316.

42. Garland SJ, Gray VL, Knorr S. Muscle activation patterns and postural control following stroke. *Motor Control*. 2009;13(4):387-411.

43. Lamontagne A, Stephenson JL, Fung J. Physiological evaluation of gait disturbances post stroke. *Clinical Neurophysiology*. 2007;118(4):717-729.

44. Patterson KK, Parafianowicz I, Danells CJ, et al. Gait asymmetry in community-ambulating stroke survivors. *Arch Phys Med Rehabil*. 2008;89(2):304-310.

45. Yu E, Abe M, Masani K, et al. Evaluation of postural control in quiet standing using center of mass acceleration: Comparison among the young, the elderly, and people with stroke. *Arch Phys Med Rehabil*. 2008;89(6):1133-1139.

46. Brunt D, Vander Linden DW, Behrman AL. The relation between limb loading and control parameters of gait initiation in persons with stroke. *Archives of Physical Medicine & Rehabilitation*. 1995;76(7):627-634.

47. Kirker SG, Simpson DS, Jenner JR, Wing AM. Stepping before standing: Hip muscle function in stepping and standing balance after stroke. *J Neurol Neurosurg Psychiatry*. 2000;68(4):458-464.

48. Hajela N. *Evoked human cutaneous reflexes during standing and step initiation.* [PhD Dissertation]. University of Minnesota; 2010.

49. Burleigh-Jacobs A, Horak FB, Nutt JG, Obeso JA. Step initiation in parkinson's disease: Influence of levodopa and external sensory triggers. *Movement Disorders*. 1997;12(2):206-215.

50. Watkins CL, Leathley MJ, Gregson JM, Moore AP, Smith TL, Sharma AK. Prevalence of spasticity post stroke. *Clinical Rehabilitation*. 2002;16(5):515-522.

51. Lundström E, Terént A, Borg J. Prevalence of disabling spasticity 1 year after first-ever stroke. *European Journal of Neurology*. 2008;15(6):533-539.

52. Bohannon RW, Smith MB. Interrater reliability of a modified ashworth scale of muscle spasticity. *Physical Therapy*. 1987;67(2):206-207.

53. Ansari NN, Naghdi S, Arab TK, Jalaie S. The interrater and intrarater reliability of the modified ashworth scale in the assessment of muscle spasticity: Limb and muscle group effect. *NeuroRehabilitation*. 2008;23(3):231-237.

54. Blackburn M, van Vliet P, Mockett SP. Reliability of measurements obtained with the modified ashworth scale in the lower extremities of people with stroke. *Physical Therapy*. January 2002;82(1):25-34.

55. Norkin C, White D. Chapter 10: The ankle and foot. In: Biblis M, ed. *Measurement of joint motion. A guide to goniometry.* 3rd ed. Philadelphia: F.A.Davis Company; 2003:225-227.

56. Martin RL, McPoil TG. Reliability of ankle goniometric measurements: A literature review. *J Am Podiatr Med Assoc*. 2005;95(6):564-572.

57. Elveru RA, Rothstein JM, Lamb RL. Goniometric reliability in a clinical setting. *Physical Therapy*. 1988;68(5):672-677.

58. Gajdosik RL, Bohannon RW. Clinical measurement of range of motion. *Physical Therapy*. 1987;67(12):1867-1872.

59. Gutman SA, Schonfeld AB. *Screening adult neurologic populations (rheumatologic rehabilitation series.* 1 <Format> Illustrated ed. Aota Press <SKU> mon0000029173; 2003:95.

60. Tinetti ME, Richman D, Powell L. Falls efficacy as a measure of fear of falling. *J Gerontol*. 1990;45(6):P239-P243.

61. Hill KD, Schwarz JA, Kalogeropoulos AJ, Gibson SJ. Fear of falling revisited. *Arch Phys Med Rehabil*. 1996;77(10):1025-1029.

62. Schmid A, Van Puymbroeck M, Altenburger P, et al. Balance and balance self-efficacy are associated with activity and participation after stroke: A cross-sectional study in people with chronic stroke. *Arch Phys Med Rehabil*. 2012;93(6):1101-1107.

63. Washburn, Richard Zhu, Weimo McAuley, Edward Frogley,Michael Figoni, Stephen. The physical activity scale for individuals with physical disabilities: Development and evaluation. *Arch Phys Med Rehabil*. 2002;83(2):193-200.

64. Washburn, R A Smith, K W Jette, A M Janney,C A. The physical activity scale for the elderly (PASE): Development and evaluation. *J Clin Epidemiol*. 1993;46(2):153-162.

65. Schuit, A J Schouten, E G Westerterp, K R Saris,W H. Validity of the physical activity scale for the elderly (PASE): According to energy expenditure assessed by the doubly labeled water method. *J Clin Epidemiol*. 1997;50(5):541-546.

66. Washburn, R A McAuley, E Katula, J Mihalko, S L Boileau,R A. The physical activity scale for the elderly (PASE): Evidence for validity. *J Clin Epidemiol*. 1999;52(7):643-651.

67. Cervantes CP, David. Physical activity measurement among individuals with disabilities: A literature review. *Adapted physical activity quarterly*. 2010;27(3):173-190.

68. Kowalski, Kristina Rhodes, Ryan Naylor, Patti-Jean Tuokko,Holly MacDonald, Stuart. Direct and indirect measurement of physical activity in older adults: A systematic review of the literature. *The international journal of behavioral nutrition and physical activity*. 2012;9:148-148.

69. van den Berg-Emons RJ, L'Ortye AA, Buffart LM, et al. Validation of the physical activity scale for individuals with physical disabilities. *Arch Phys Med Rehabil*. 2011;92(6):923-928.

70. Ainslie, Philip Reilly,Thomas Westerterp, Klass. Estimating human energy expenditure: A review of techniques with particular reference to doubly labelled water. *Sports medicine*. 2003;33(9):683-698.

71. Leenders NYJM, W M Sherman,H N Nagaraja. Comparisons of four methods of estimating physical activity in adult women. *Med Sci Sports Exerc*. 2000;32(7):1320-1326.

72. Hensel A, Angermeyer MC, Riedel-Heller SG. Measuring cognitive change in older adults: Reliable change indices for the mini-mental state examination. *Journal of Neurology, Neurosurgery & Psychiatry*. 2007;78(12):1298-1303.

73. Mitrushina M, Satz P. Reliability and validity of the mini-mental state exam in neurologically intact elderly. *J Clin Psychol*. 1991;47(4):537-543.

74. Mungas D. In-office mental status testing: A practical guide (review). *Geriatrics*. 1991;46(7):54-8-63,66.

75. Fugl Meyer AR, JÃƒÂ¤ÃƒÂ¤skÃƒÂ¶ L, Leyman I, Olsson S, Steglind S. The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance. *Scand J Rehabil Med*. 1975;7(1):13-31.

76. Dettmann MA, Linder MT, Sepic SB. Relationships among walking performance, postural stability, and functional assessments of the hemiplegic patient. *Am J Phys Med*. 1987;66(2):77-90.

77. Hass CJ, Waddell DE, Wolf SL, Juncos JL, Gregor RJ. Gait initiation in older adults with postural instability. *Clin Biomech*. 2008;23(6):743-753.

78. McIlroy, W E Maki,B E. Changes in early 'automatic' postural responses associated with the prior-planning and execution of a compensatory step. *Brain Res*. 1993;631(2):203-211.

79. Liu W, Kim SH, Long JT, Pohl PS, Duncan PW. Anticipatory postural adjustments and the latency of compensatory stepping reactions in humans. *Neurosci Lett*. 2003;336(1):1-4.

80. Cauraugh, James Naik, Sagar Lodha, Neha Coombes,Stephen Summers, Jeffery. Long-term rehabilitation for chronic stroke arm movements: A randomized controlled trial. *Clin Rehabil*. 2011;25(12):1086-1096.

81. Cauraugh, James Coombes, Stephen Lodha, Neha Naik,Sagar Summers, Jeffery. Upper extremity improvements in chronic stroke: Coupled bilateral load training. *Restorative Neurol Neurosci*. 2009;27(1):17-25.

82. Rogers MW, Hedman LD, Johnson ME, Martinez KM, Mille M. Triggering of protective stepping for the control of human balance: Age and contextual dependence. *Cognitive Brain Research*. 2003;16(2):192-198.

83. Mansfield, Avril Inness, Elizabeth Komar, Janice Biasin, Louis Brunton, Karen Lakhani,Bimal McIlroy, William. Training rapid stepping responses in an individual with stroke. *Phys Ther*. 2011;91(6):958-969.

84. Mansfield, Avril Peters, Amy Liu,Barbara Maki, Brian. Effect of a perturbation-based balance training program on compensatory stepping and grasping reactions in older adults: A randomized controlled trial. *Phys Ther*. 2010;90(4):476-491.

85. Jöbges, M Heuschkel, G Pretzel, C Illhardt, C Renner,C Hummelsheim, H. Repetitive training of compensatory steps: A therapeutic approach for postural instability in parkinson's disease. *Journal of neurology, neurosurgery and psychiatry*. 2004;75(12):1682-1687.

86. Patchay S, Gahery Y, Serratrice G. Early postural adjustments associated with gait initiation and age-related walking difficulties. *Movement Disorders*. 2002;17(2):317-326.

87. Behrman AL, Bishop MD, Ko M. Effects of limb loading on gait initiation in persons with moderate hemiparesis. *Topics in Stroke Rehabilitation*. 2011;18:258.

88. Henriksson M, Hirschfeld H. Physically active older adults display alterations in gait initiation. *Gait Posture*. 2005;21(3):289-296.

89. Wall, J C Turnbull,G I. Gait asymmetries in residual hemiplegia. *Arch Phys Med Rehabil*. 1986;67(8):550-553.

90. Shumway Cook, A Anson,D Haller, S. Postural sway biofeedback: Its effect on reestablishing stance stability in hemiplegic patients. *Arch Phys Med Rehabil*. 1988;69(6):395-400.

91. Bohannon, R W Larkin,P A. Lower extremity weight bearing under various standing conditions in independently ambulatory patients with hemiparesis. *Phys Ther*. 1985;65(9):1323-1325.

92. Feigin VL, Lawes CM, Bennett DA, Barker-Collo SL, Parag V. Worldwide stroke incidence and early case fatality reported in 56 population-based studies: A systematic review. *The Lancet Neurology*. 2009;8(4):355-369.

93. Demaerschalk BM, Hwang H, Leung G. US cost burden of ischemic stroke: A systematic literature review. *Am J Manag Care*. 2010;16(7):525-533.

94. Jørgensen HS, Nakayama H, Raaschou HO, Olsen TS. Recovery of walking function in stroke patients: The copenhagen stroke study. *Arch Phys Med Rehabil*. 1995;76(1):27-32.

95. Michael K, Macko RF. Ambulatory activity intensity profiles, fitness, and fatigue in chronic stroke. *Topics in Stroke Rehabilitation*. 2007;14(2):5-12.

96. Michael KM, Allen JK, Macko RF. Fatigue after stroke: Relationship to mobility, fitness, ambulatory activity, social support, and falls efficacy. *Rehabilitation Nursing*. 2006;31(5):210-217.

97. Michael KM, Allen JK, Macko RF. Reduced ambulatory activity after stroke: The role of balance, gait, and cardiovascular fitness. *Archives of Physical Medicine & Rehabilitation*. 2005;86(8):1552-1556.

98. Pang MY, Eng JJ, Dawson AS. Relationship between ambulatory capacity and cardiorespiratory fitness in chronic stroke: Influence of stroke-specific impairments. *Chest*. 2005;127(2):495-501.

99. Pang MY, Eng JJ, McKay HA, Dawson AS. Reduced hip bone mineral density is related to physical fitness and leg lean mass in ambulatory individuals with chronic stroke. *Osteoporosis Int*. 2005;16(12):1769-1779.

Appendices

Appendix A

Stroke Stepping Study

A research study investigating the ability to take a step given different "go" cues is being conducted at the University of Minnesota program in Rehabilitation Science. The study involves receiving a non-painful stimulus of a nerve in the leg.

Study requirements:

1. History of stroke at least 3 months ago
2. >18 years of age
3. Able to walk by yourself within your home and/or community (may use assistive device and/or leg brace)
4. Able to understand and respond to directions
5. Able to attend one session – lasting approximately 2 ½ hours

If you are interested in finding out more about the study and whether or not you would qualify to participate, please contact Megan Dowdal-Osborn,PT at 612-626-2443 or dowd0021@umn.edu

Appendix B

Modified Ashworth Scale

Grade	Description
0	No increase in muscle tone
1	Slight increase in muscle tone, manifested by a catch or by minimal resistance at the end of the range of motion (ROM) when the affected part(s) is moved in flexion or extension
1+	Slight increase in muscle tone, manifested by a catch, followed by minimal resistance throughout the remainder (less than half) of the ROM
2	More marked increase in muscle tone through most of the ROM, but affected part(s) easily moved
3	Considerable increase in muscle tone, passive movement difficult
4	Affected part(s) rigid in flexion or extension

Appendix C

Modified Falls Efficacy Scale *

How confident are you that you can do each of the following activities WITHOUT falling? Use the scale below.

0 = not confident at all **5 = fairly confident** **10 = completely** confident

1.	Get dressed and undressed	0	1	2	3	4	5	6	7	8	9	10
2.	Prepare a simple meal	0	1	2	3	4	5	6	7	8	9	10
3.	Take a bath or shower	0	1	2	3	4	5	6	7	8	9	10
4.	Get in/out of a chair	0	1	2	3	4	5	6	7	8	9	10
5.	Get in/out of bed	0	1	2	3	4	5	6	7	8	9	10
6.	Answer the door or telephone	0	1	2	3	4	5	6	7	8	9	10
7.	Walk around inside of your house	0	1	2	3	4	5	6	7	8	9	10
8.	Reach into cabinets or closet	0	1	2	3	4	5	6	7	8	9	10
9.	Light housekeeping	0	1	2	3	4	5	6	7	8	9	10
10.	Simple shopping	0	1	2	3	4	5	6	7	8	9	10
11.	Using public transportation	0	1	2	3	4	5	6	7	8	9	10
12.	Crossing roads	0	1	2	3	4	5	6	7	8	9	10
13.	Light gardening or hanging out wash	0	1	2	3	4	5	6	7	8	9	10
14.	Using front or rear steps at home	0	1	2	3	4	5	6	7	8	9	10

Raw Score = _____/140

Average Score = _____

*Modified from Hill KD, Schwartz JA, Kalogeropolous AJ, Gibson SJ. Fear of Falling Revisited. *Arch Phys Med Rehabil*. 1996;77:1025-1029.

Appendix D

Physical Activity Scale in Persons with Disabilities (PASIPD)*

Instructions: This questionnaire is about your current level of physical activity and exercise. Please remember there are no right or wrong answers. We simply need to assess your current level of activity.

Leisure Time Activity

1. During the past 7 days how often did you engage in stationary activities such as reading, watching TV, computer games, or doing handcrafts?
1. Never (Go to question #2)
2. Seldom (1–2d)
3. Sometimes (3–4d)
4. Often (5–7d)

On average, how many hours per day did you spend in these stationary activities?
1. Less than 1hr
2. 1 but less than 2hr
3. 2–4hr
4. More than 4hr

2. During the past 7 days, how often did you walk, wheel, push outside your home other than specifically for exercise.
For example, getting to work or class, walking the dog
shopping, or other errands?
1. Never (Go to question #3)
2. Seldom (1–2d)
3. Sometimes (3–4d)
4. Often (5–7d)

On average, how many hours per day did you spend wheeling or pushing outside your home?
1. Less than 1hr
2. 1 but less than 2hr
3. 2–4hr
4. More than 4hr

3. During the past 7 days, how often did you engage in light sport or recreational activities such as bowling, golf with a cart, hunting or fishing, darts, billiards or pool, therapeutic exercise (physical or occupational therapy, stretching, use
of a standing frame) or other similar activities?
1. Never (Go to question #4)
2. Seldom (1–2d)

3. Sometimes (3–4d)
4. Often (5–7d)

On average, how many hour per day did you spend in these light sport or recreational activities?
1. Less than 1hr
2. 1 but less than 2hr
3. 2–4hr
4. More than 4hr

4. During the past 7 days, how often did you engage in moderate sport and recreational activities such as doubles tennis, softball, golf without a cart, ballroom dancing, wheeling or pushing for pleasure or other similar activities?
1. Never (Go to question #5)
2. Seldom (1–2d)
3. Sometimes (3–4d)
4. Often (5–7d)

On average, how many hours per day did you spend in these moderate sport and recreational activities?
1. Less than 1hr
2. 1 but less than 2hr
3. 2–4hr
4. More than 4hr

5. During the past 7 days, how often did you engage in strenuous sport and recreational activities such as jogging,
wheelchair racing (training), off-road pushing, swimming, aerobic dance, arm cranking, cycling (hand or leg), singles tennis, rugby, basketball, walking with crutches and braces, or other similar activities
1. Never (Go to question #6)
2. Seldom (1–2d)
3. Sometimes (3–4d)
4. Often (5–7d)

On average, how many hours per day did you spend in these strenuous sport or recreational activities?
1. Less than 1hr
2. 1 but less than 2hr
3. 2–4hr
4. More than 4hr

6. During the past 7 days, how often did you do any exercise specifically to increase muscle strength and endurance
such as lifting weights, push-ups, pull-ups, dips, or wheelchair push-ups, etc?
1. Never (Go to question #7)
2. Seldom (1–2d)

3. Sometimes (3–4d)
4. Often (5–7d)

On average, how many hours per day did you spend in these exercises to increase muscle strength and endurance?
1. Less than 1hr
2. 1 but less than 2hr
3. 2–4hr
4. More than 4hr

Household Activity

7. During the past 7 days, how often have you done any light housework, such as dusting, sweeping floors or washing dishes?
1. Never (Go to question #8)
2. Seldom (1–2d)
3. Sometimes (3–4d)
4. Often (5–7d)

On average, how many hours per day did you spend doing light housework?
1. Less than 1hr
2. 1 but less than 2hr
3. 2–4hr
4. More than 4hr

8. During the past 7 days, how often have you done any heavy housework or chores such as vacuuming, scrubbing floors, washing windows, or walls, etc?
1. Never (Go to question #9)
2. Seldom (1–2d)
3. Sometimes (3–4d)
4. Often (5–7d)

On average, how many hours per day did you spend doing heavy housework or chores?
1. Less than 1hr
2. 1 but less than 2hr
3. 2–4hr
4. More than 4hr

9. During the past 7 days, how often you done home repairs like carpentry, painting, furniture refinishing, electrical work, etc?
1. Never (Go to question #10)
2. Seldom (1–2d)
3. Sometimes (3–4d)
4. Often (5–7d)

On average, how many hours per day did you spend doing home repairs?
1. Less than 1hr
2. 1 but less than 2hr

3. 2–4hr
4. More than 4hr

10. During the past 7 days how often have you done or yard care including mowing, leaf or snow removal, tree or bush trimming, or wood chopping, etc?
1. Never (Go to question #11)
2. Seldom (1–2d)
3. Sometimes (3–4d)
4. Often (5–7d)

On average, how many hours per day did you spend doing lawn work?
1. Less than 1hr
2. 1 but less than 2hr
3. 2–4hr
4. More than 4hr

11. During the past 7 days, how often have you done outdoor gardening?
1. Never (Go to question #12)
2. Seldom (1–2d)
3. Sometimes (3–4d)
4. Often (5–7d)

On average, how many hours per day did you spend doing outdoor gardening?
1. Less than 1hr
2. 1 but less than 2 hr
3. 2–4hr
4. More than 4hr

12. During the past 7 days, how often did you care for another person, such as children, a dependent spouse, or another adult?
1. Never (Go to question #13)
2. Seldom (1–2d)
3. Sometimes (3–4d)
4. Often (5–7d)

On average, how many hours per day did you spend caring for another person?
1. Less than 1hr
2. 1 but less than 2hr
3. 2–4hr
4. More than 4hr

Work-Related Activity

13. During the past 7 days, how often did you work for pay or as a volunteer ? (Exclude work that mainly involved sitting with slight arm movement such as light office work, computer work, light assembly line work, driving bus or van, etc.)
1. Never (Go to END)
2. Seldom (1–2d)

3. Sometimes (3–4d)
4. Often (5–7d)

On average, how many hours per day did you spend working for pay or as a volunteer?
1. Less than 1hr
2. 1 but less than 4hr
3. 5 but less than 8hr
4. 8hr or more

*Modified from Washburn et al. The physical activity scale for individuals with physical disabilities: Development and evaluation. *Arch Phys Med Rehabil*. 2002;83(2):193-200.

Appendix E

Mini Mental State Examination (MMSE)*

Orientation	Score	
1. What is the year?	0	1
2. What is the season?	0	1
3. What month is it now?	0	1
4. What day of the week is it today?	0	1
5. What is the date today?	0	1
6. What country are we in?	0	1
7. What city/town are we in?	0	1
8. What suburb are we in?	0	1
9. What building are we in now?	0	1
10. What ward/room/floor of the building are we in?	0	1

Registration

1. Listen carefully. I'm going to say three words. Please repeat all three word after me.

   APPLE COIN CHAIR 0 1 2 3 4

   Now, keep those words in mind. I will be asking you to say them again in a few minutes.

Attention and Calculation

1. Please subtract down from 100 by 7's. Subtract 7 from 100 and continue on until I tell you to stop.

   Record Responses ____ ____ ____ ____ ____ 0 1 2 3 4 5

Recall

1. What were the three words I asked you to remember?

Record Responses _____ 0 1 2 3

Naming

1. What is this (point to pen/pencil) 0 1
2. What it this (point to a watch) 0 1

Repetition

1. Listen carefully. I'm going to ask you to repeat what I say. "The pastry cook was elated" 0 1

Comprehension

1. Listen carefully. I'm going to ask you to do something.
   Take this piece of paper in your right/left (non-dominant or less affected hand)
   0 1
   fold it in half and 0 1
   place it on the floor. 0 1

Reading

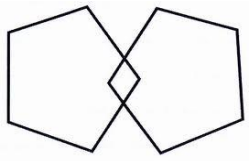
1. Please read this and do as it says. (CLOSE YOUR EYES) 0 1

Writing

1. Please write me a complete sentence (subject, verb, makes sense) 0 1

Drawing

1. Please copy this picture 0 1



*Modified from Folstein et al. "Mini-mental State": A practical guide for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*. 1975; 12: 189-198

Appendix F

Fugl-Meyer Lower Extremity Assessment of Motor Function*

Position	Test	Score	Scoring Criterea
Supine	Reflex Activity	Patellar _____ Achilles _____	None = 0 Can be elicited = 2
Supine	Volitional movement within synergy	**Flexor Synergy** Hip Flexion_____ Knee Flexion_____ Ankle DF_____ **Extensor Synergy (resisted motion)** Hip Extension_____ Hip Adduction_____ Knee Extension_____ Ankle PF_____	No motion = 0 Partial motion = 1 Full motion = 2 No motion = 0 Weak motion = 1 Normal strength = 3
Sitting (knee clear of chair)	Volitional movement, mixing synergies	Knee flexion >90°___ Ankle DF_____	No active motion = 0 Knee slightly extended, can be flexed but not beyond 90° = 1 No active DF = 0 Incomplete active DF = 1 Normal DF = 2
Standing (hip at 0°)	Volitional movement without synergy	Knee Flexion_____	No active knee flexion without hip flexion = 0 Knee begins flexion without hip flexion, <90° or hip flexes during motion = 1 Full knee flexion without hip flexion = 2

		DF_____	No active motion = 0 Partial motion = 1 Full motion = 2
Supine	Reflex activity	Knee Flexors_____ Patellar_____ Achilles_____	2 of the 3 are markedly hyperactive = 0 One reflex is hyperactive or 2 reflexes are lively = 1 No more than 1 reflex lively = 2
Supine	Coordination/Speed (heel to knee of opposite leg in rapid succession)	Tremor_____ Dysmetria_____ Time_____	Marked = 0 Slight = 1 None = 2 Pronounced and unsystematic = 0 Slight and systematic = 1 None = 2 >5 sec = 0 2-5 sec = 1 <1 sec = 2
		Total Score ____/34	

*Modified from Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S. The post stroke hemiplegic patient. I. A method for evaluation of physical performance. *Scand J Rehabil Med* 1975;7:13-31.

Appendix G

Phone script for research candidates

"If you are agreeable, I need to ask you some questions to help determine if you are eligible to participate in this study. Upon completion of these questions, if you are eligible, you will be invited to participate in the study."

1. What is your age?
2. When was your stroke?
3. Are you able to walk around your home and/or your community by yourself?
4. Do you wear a brace? If so, are you able to take 3 steps without the brace unassisted?
5. Are you able to see clearly 4-5 feet in front of you with or without glasses?
6. Do you have double vision?
7. Do you have any orthopedic history that makes stepping difficult?
8. Do you have any implanted, active medical devices?
9. Have you had Botox or Phenol injections into your legs in the past 6 months?

Appendix H

CONSENT FORM

Effects of non-noxious sural nerve stimulation on reflex response modulation in ipsilateral tibialis anterior and gluteus medius muscles during step initiation in a stroke population.

You are invited to be in a research study concerned with how you take a step when prompted by different cues. You are selected as a possible participant because you had a stroke in the past and you responded to the announcement of the study. We ask that you read this form and ask any questions you may have before agreeing to be in the study.

This study is being conducted by: Megan Dowdal-Osborn, Graduate student, Program in Rehabilitation Sciences, Department of Physical Medicine and Rehabilitation at the University of Minnesota.

Background Information

The purpose of this study is to examine how reflexes that are activated by sensory nerves supplying the skin of the feet are affected during step initiation. In doing this experiment we are hoping to better understand the role of reflexes in persons who have had a stroke in activating the appropriate muscles needed to take a step.

Procedure

If you agree to be in this study, you will be asked to do the following things:

1) Provide background information to the investigator about your age, height, weight, current medications, and any history of orthopedic disorders that affect your ability to take a step.
2) Complete the following assessment tools: Modified Ashworth scale of muscle tone (your ankles and legs will be passively moved up and down by manual assist); ankle range of motion (your ankle movement will be measured); leg strength (you will demonstrate the strength of leg movements against a manual resistance), Mini-Mental examination (you will be asked to respond to a series of questions/tasks relating to memory, sequencing, verbal articulation); visual field screen (you will be asked to respond to finger movements in your peripheral visual field to check your vision); sensory testing (you will be asked to respond to whether or not you can feel light touches on your lower leg and foot); Physical Activity Scale (you will be asked to respond to questions related to your general physical activity); Falls Efficacy Scale (you will be asked to respond to questions related to how concerned you are about falling while doing certain activities););

Fugl-Meyer LE motor assessment (you will be ask to perform various leg movements to the best of your abilities)

3) Have bandage like electrodes placed on the skin overlying two muscles, a muscle on the right side of the shin bone and one near your hip.
4) Allow stimulation to the sural nerve - a nerve that runs underneath the outside aspect of the ankle.
5) Stand with a harness secured and both feet on a separate force platform with weight equally distributed. The harness provides support in the event of a loss of balance and is placed over your head, wraps around your trunk and is secured with straps around each leg. It is secured overhead and has the flexibility to move with you on each step. You will need to stand in bare feet – no braces or shoes are allowed for the testing. A ready cue (red light) will be followed at 1-2 second random intervals by a "go" cue. When given the "go" cue, you are asked to take 3 steps as quickly as you can. The "go" cue will be either a second visual cue or a stimulation to the sural nerve. You will go through 30 stepping trials per leg for a total of 60 stepping trials.
6) You will receive a 5 minute seated rest break after the initial 30 stepping trials.
7) All electrodes will be removed at the end of the session. The testing does not involve any invasive procedures. The entire session will last approximately 2 1/2 hours.

Risks of Study Participation

The study has some minimal risks: First, the nerve stimulation requires us to use an electrical device that delivers a pulse to the nerve. As with any electrical devices applied to the skin there is a remote possibility of an inadvertent electrical shock due to equipment malfunction. This risk is considered to be extremely remote in that safety mechanisms have been built in to the device to eliminate such a problem. Secondly, the electric stimulator is capable of delivering very strong pulses of current. We will only use low intensities of stimulation that should feel like a tingling sensation that radiates into your foot. If the stimulus feels painful, you should inform us and the experiment would be stopped immediately.

Benefits of Study Participation

There are no benefits to you for participating in this study.

Alternatives to Participating in this Study

This study does not incorporate any treatment and therefore you may either volunteer to participate or choose not to participate.

Research Related Injury

In the event that this research activity results in an injury, treatment will be available, including first aid,emergency treatment and follow up care as needed. Care for such injuries will be billed in the ordinary manner, to you or your insurance company. If you think that you have suffered a research related injury let the study investigator immediately

Confidentiality

The records of this study will be kept private. If any of the data is published or presented it will not include any information that would make it possible to identify you as a participant. Confidentiality is not complete to the extent that records pertaining to this research may be examined by departments of the University of Minnesota with regulatory authority to assure proper conduct of the research.

Protected Health Information (PHI)

Your PHI created or received for the purposes of this study is protected under the federal regulation known as HIPAA. Refer to the attached HIPAA authorization for details concerning the use of this information.

Voluntary Nature of the Study

Your decision whether or not to participate will not affect your current or future relations with the University. If you decide to participate, you are free to withdraw at any time without affecting those relationships.

Compensation

Upon completion of your participation in this study, you may chose to be entered in a drawing for a $50.00 Target gift card. If you chose to enter the drawing, you will need to provide your name and contact information in order to be notified if your name is drawn. You may chose not to participate in the drawing. Up to 20 people will be entered in to the drawing. Costs directly associated with parking or transportation to and from the University campus from your home for the purposes of this study will be reimbursed. Compensation for transportation will not exceed $40.00

New Information:

If during the course of this research study there are significant new findings discovered which might influence your willingness to continue, the researchers will inform you of those developments.

Contacts and Questions:

The researcher conducting this study is Megan Dowdal-Osborn. You may ask any questions you have now. If you have questions later, you may contact Megan at the Program in Physical Therapy, Box 388 MMC, The University of Minnesota, Minneapolis, MN 55455. Phone: 612-626-2443 Email: dowd0021@umn.edu

You may also contact Megan's adviser, Dr. Carl Kukulka at 612-625-5022 or kukul001@umn.edu

If you have any questions or concerns regarding the study and would like to talk to someone other than the researcher(s), contact the Fairview Research Helpline at telephone number 612-672-7692 or toll free at 866-508-6961. You may also contact this office in writing or in person at Fairview Research Administration, 2433 Energy Park Drive, St. Paul MN 55108.

You will be given a copy of this form to keep for your records.

Statement of Consent:

I have read the above information. I have asked questions and have received answers. I consent to participate in the study.

Signature _____ Date_____

Signature of Person Obtaining Consent _____Date_____

Appendix I

HIPAA[1] AUTHORIZATION TO USE AND DISCLOSE INDIVIDUAL HEALTH INFORMATION FOR RESEARCH PURPOSES

1. Purpose. As a research participant, I authorize Megan Dowdal-Osborn and the researcher's staff to use and disclose my individual health information for the purpose of conducting the research project entitled : Effects of non-noxious sural nerve stimulation on reflex response modulation in ipsilateral tibialis anterior and gluteus maximus muscles during step initiation in a stroke population, [1105M99254].

2. Individual Health Information to be Used or Disclosed. My individual health information that may be used or disclosed to conduct this research includes: Test (imaging) and examination findings that describe stroke type, location, date of occurance.

3. Parties Who May Disclose My Individual Health Information.

The researcher and the researcher's staff may obtain my individual health information from other healthcare providers, such as laboratories, which are a part of this research, as well as healthcare providers that are not part of this research (other doctors, hospitals and/or clinics) for the purposes of carrying out this research study. I authorize these parties to disclose my individual health information to the researcher and the researcher's staff for the purposes of carrying out this research study.

4. Parties Who May Receive or Use My Individual Health Information. The individual health information disclosed by parties in item 3 and information disclosed by me during the course of the research may be received and used by Megan Dowdal-Osborn and the researcher's staff and the researcher's faculty advisor, Dr. Carl Kukulka

5. Right to Refuse to Sign this Authorization. I do not have to sign this Authorization. If I decide not to sign the Authorization, I may not be allowed to participate in this study or receive any research related treatment that is provided through the study. However, my decision not to sign this authorization will not affect any other treatment, payment, or enrollment in health plans or eligibility for benefits.

[1] HIPAA is the Health Insurance Portability and Accountability Act of 1996, a federal law related to privacy of health information.

6. Right to Revoke. I can change my mind and withdraw this authorization at any time by sending a written notice to Megan Dowdal-Osborn to inform the researcher of my decision (Dowdal-Osborn mailing address: MMC 388, 420 Delware Street SE, Minneapolis MN 55455). If I withdraw this authorization, the researcher may only use and disclose the protected health information already collected for this research study. No further health information about me will be collected by or disclosed to the researcher for this study.

7. Potential for Re-disclosure. Once my health information is disclosed under this authorization, there is a potential that it will be re-disclosed outside this study and no longer covered by this authorization. However, the research team and the University's Institutional Review Board (the committee that reviews studies to be sure that the rights and safety of study participants are protected) are very careful to protect your privacy and limit the disclosure of identifying information about you.

7A. Also, there are other laws that may require my individual health information to be disclosed for public purposes. Examples include potential disclosures if required for mandated reporting of abuse or neglect, judicial proceedings, health oversight activities and public health measures.

This authorization does not have an expiration date.

I am the research participant or personal representative authorized to act on behalf of the participant.

I have read this information, and I will receive a copy of this authorization form after it is signed.

_____ _____

signature of research participant or research participant's personal representative — date

_____

printed name of research participant or research participant's personal representative — description of personal representative's authority to act on behalf of the research participant

Appendix J

Subject_____

Date_____

Age_____

Weight_____

1.5 RT_____

Initial stepping leg: R L

Initial go cue: V S

Date of stroke_____

Location of stroke_____

Use of AFO Y or N (if yes: R or L)

Use of AD

_____

Modified Ashworth Score	Right	Left
Hip flexion		
Hip extension		
Hip adduction		
Knee flexion		
Knee extension		
DF		
PF		

0 No increase in tone

1 Slight increase in muscle tone, manifested by a catch and release or minimal resistance at the end of the ROM when the affected part(s) is moved in flexion or extension

1+ Slight increase in muscle tone, manifested by a catch, followed by minimal resistance throughout the remainder (less than half) of the ROM

2 More marked increase in muscle tone through most of the ROM, but affected part(s) easily moved

3 Considerable increase in muscle tone, passive movement difficult

4 Affected part(s) rigid in flexion or extension

MMT	Right	Left
Hip flexion		
Hip extension		
Hip Adduction		
Knee flexion		
Knee extension		
DF		
PF		

AAROM	Right	Left
DF		
PF		

Sensory testing

Right: _____/10

Left: _____/10

Subjective Comments:

Appendix K

Subject	Age	Sex	Stroke Location	Years from Stroke	Hemiparesis	MM	mFES raw score(140)	mFES avg score (10)	PASIPD	FM-motor only (34)	RT (P/NP)
1	78	F	internal capsule	2	Right	29	135	9.6	15.2	28	1.1/1.1
2	76	M	internal capsule	12	Left	28	139	9.7	14.2	32	3.3/2.3
3	59	M	MCA	2	Right	15	135	9.6	9.8	30	2.5/2.2
4	60	M	MCA	14	Left	28	130	9.3	14.7	25	1.2/1.2
5	58	F	ACA	5	Left	30	106	7.6	16.1	33	1.6/1.6
6	35	F	MCA	2	Right	28	118	8.5	11.6	20	1.6/1.2
7	75	M	Right Temporal	4	Left	29	116	8.3	25.8	26	1.4/2.1
8	50	F	MCA	13	Left	27	111	7.9	22.7	34	2.3/3.2
9	48	M	MCA	15	Left	30	139	9.9	22.6	18	3.3/3.3
10	83	M	MCA	9	Right	27	131	9.4	10.5	20	.9/1.2
11	59	M	ACA	7	Left	30	140	10	33.4	22	2.4/2.6
12	84	F	Right Insula	20	Left	26	108	7.7	0.7	29	1/2.4
13	75	M	Right Parietal Hem	4	Left	28	121	8.6	2.6	32	2.3/2
14	56	F	Right MCA	14	Left	30	129	9.2	40.4	33	.75/.9
15	72	M	(L)parietal/periventricular	1	Right	27	140	10	30.7	31	1.8/1.8

Appendix L

Net Xp

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Condition	1	1562.735123	1562.735123	1.33	0.2539
Step_Limb	1	5125.323517	5125.323517	4.36	0.0413

Net Yp

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Condition	1	5.02645824	5.02645824	0.06	0.8081
Step_Limb	1	6.08799046	6.08799046	0.07	0.7892

Xp onset

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Condition	1	457319.9613	457319.9613	106.96	<.0001
Step_Limb	1	2291.1057	2291.1057	0.54	0.4672

Yp onset

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Condition	1	425899.0683	425899.0683	85.15	<.0001
Step_Limb	1	24.2997	24.2997	0.00	0.9447

Δ Mx

Source	DF	Type III SS	Mean Square	F Value	Pr > F
leg_condition	1	62.76328679	62.76328679	10.26	0.0018
Condition	1	0.01832981	0.01832981	0.00	0.9564
Step_Limb	1	16.53428774	16.53428774	2.70	0.1028

ΔMy

Source	DF	Type III SS	Mean Square	F Value	Pr > F
leg_condition	1	3.22993006	3.22993006	3.17	0.0776
Condition	1	1.24363186	1.24363186	1.22	0.2716
Step_Limb	1	0.79902001	0.79902001	0.78	0.3777

Net Yp with Symmetry Variable

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Diff_Base_Fz	1	844.5663148	844.5663148	10.68	0.0029
Condition	1	1.0776238	1.0776238	0.01	0.9079

Yp onset with symmetry variable

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Diff_Base_Fz	1	21175.0341	21175.0341	4.68	0.0396
Condition	1	180299.8310	180299.8310	39.81	<.0001

TA reaction time

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Condition	1	607768.7987	607768.7987	63.00	<.0001
Step_Limb	1	214.7222	214.7222	0.02	0.8819
leg_cond	1	2975.4573	2975.4573	0.31	0.5806

Paretic TA EMG

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Condition	1	2007.36574	2007.36574	0.29	0.5942
Step_Limb	1	92451.53360	92451.53360	13.48	0.0014

Non-Paretic TA EMG

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Condition	1	196.92620	196.92620	0.08	0.7840
Step_Limb	1	32995.34181	32995.34181	12.76	0.0009

GM EMG

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Condition	1	65.99874531	65.99874531	0.18	0.6747
Step_Limb	1	0.03768941	0.03768941	0.00	0.9920

GM Reaction Time

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Condition	1	341247.3077	341247.3077	69.94	<.0001
Step_Limb	1	6176.0947	6176.0947	1.27	0.2698

Fz Reaction Time

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Step_Limb	1	9576.3387	9576.3387	2.38	0.1255
Condition	1	985576.5997	985576.5997	245.08	<.0001
action	1	256.5466	256.5466	0.06	0.8010

dFz/dt (action = loading)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Condition	1	29309.00124	29309.00124	4.34	0.0417
Step_Limb	1	37136.05915	37136.05915	5.50	0.0225

dFz/dt (action = unloading)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Condition	1	24706.70181	24706.70181	3.17	0.0804
Step_Limb	1	49861.91938	49861.91938	6.40	0.0142

dFz/dt (limb = paretic)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
action	1	32446.61371	32446.61371	4.86	0.0316
Condition	1	26335.54333	26335.54333	3.94	0.0519

dFz/dt (limb = non-paretic)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
action	1	55637.28719	55637.28719	7.07	0.0102
Condition	1	27589.23648	27589.23648	3.50	0.0663

Loading Amount (action = loading)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Condition	1	58.4568089	58.4568089	0.84	0.3622
Step_Limb	1	339.9441645	339.9441645	4.91	0.0308

Loading Amount vs. Symmetry Variable

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Diff_Base_Fz	1	494.4093544	494.4093544	6.98	0.0135
Condition	1	55.1009650	55.1009650	0.78	0.3855

dFz/dt vs. Symmetry Variable

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Diff_Base_Fz	1	63138.13789	63138.13789	8.53	0.0070
Condition	1	29585.46943	29585.46943	4.00	0.0558

Symmetry Random Effects

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Leg_Cond	1	2467.395426	2467.395426	290.88	<.0001
Subject	14	0.000000	0.000000	0.00	1.0000
Leg_Cond*Subject	14	4754.140088	339.581435	40.03	<.0001